The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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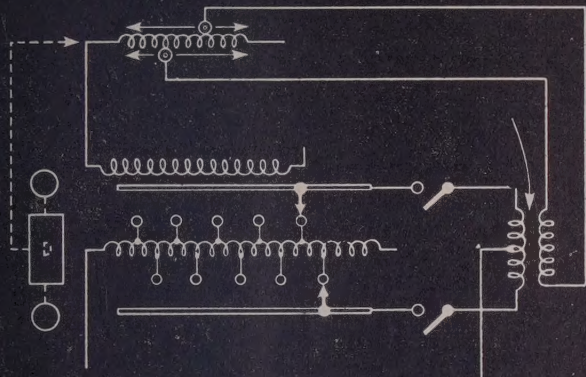W. K. BRASHER, C.B.E., M.A., M.I.E.E.

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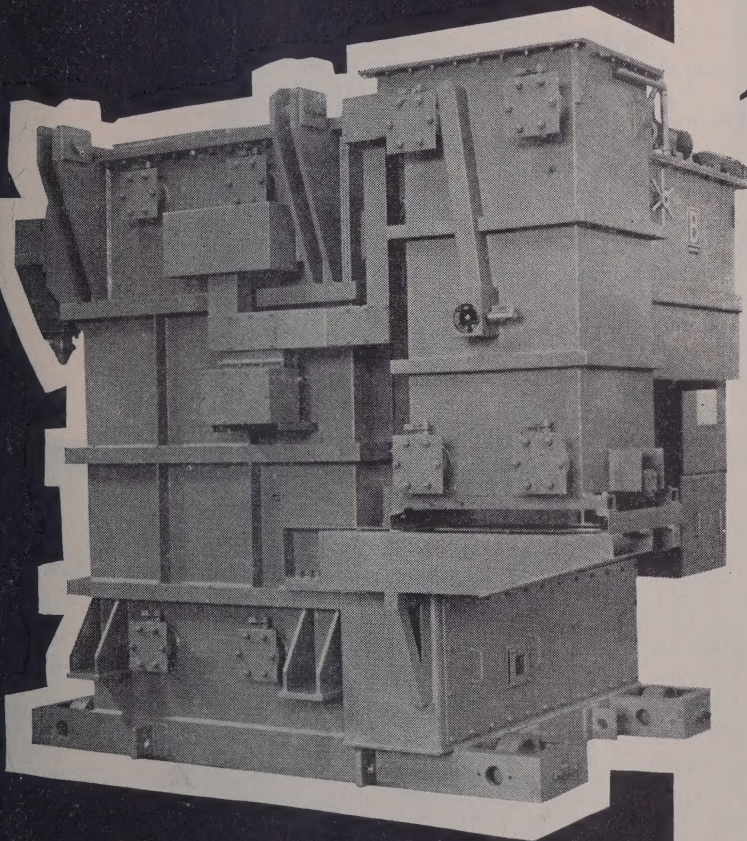
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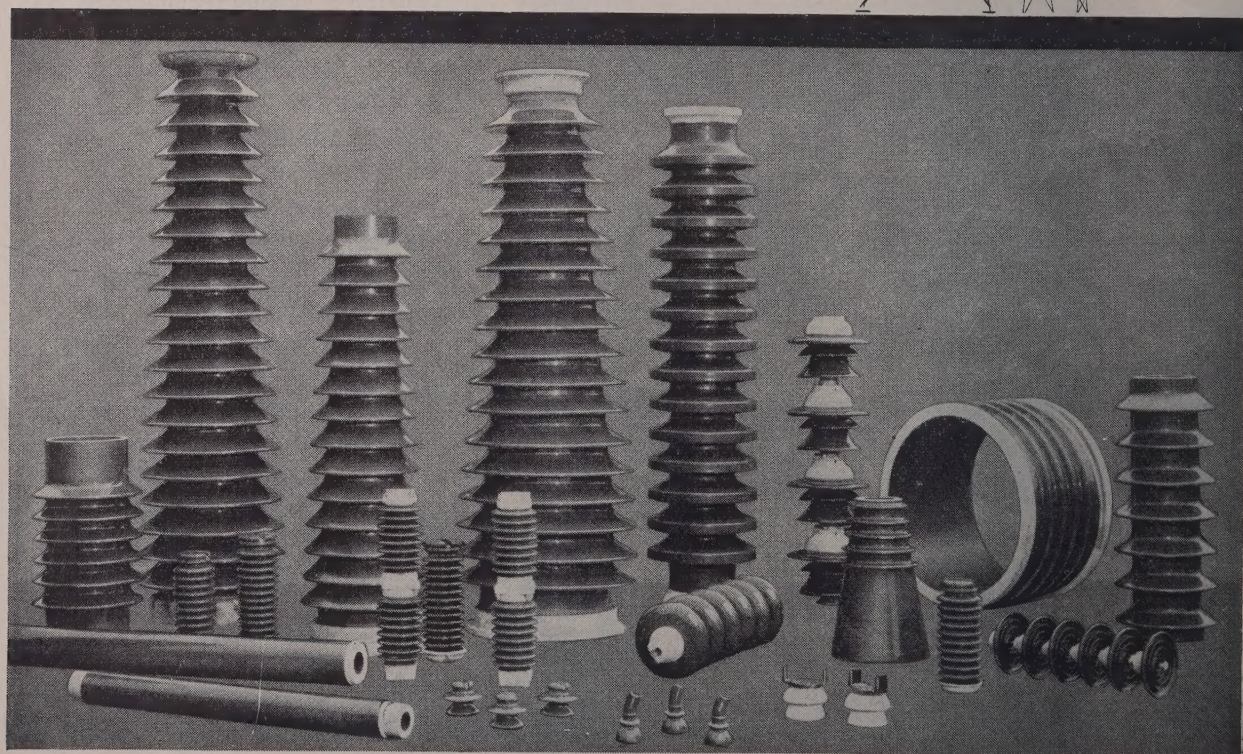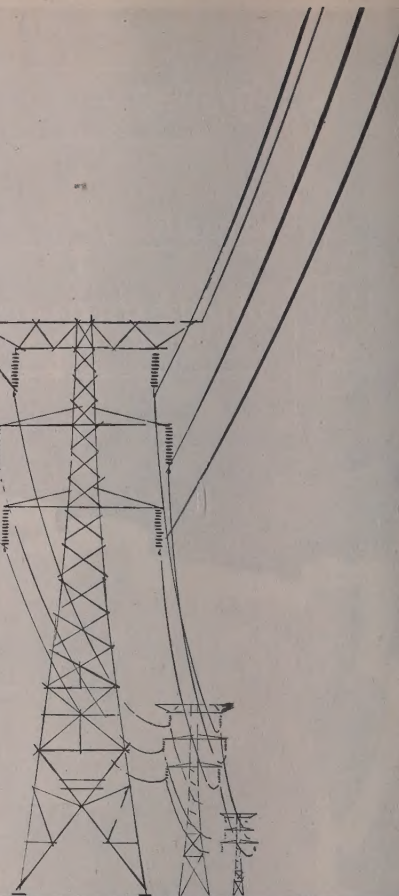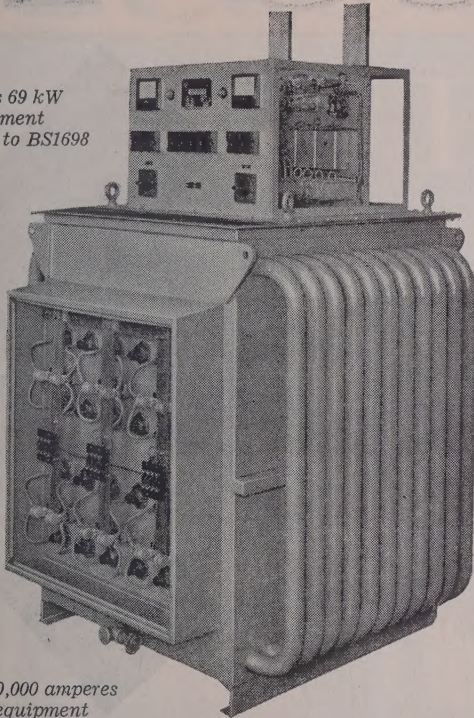

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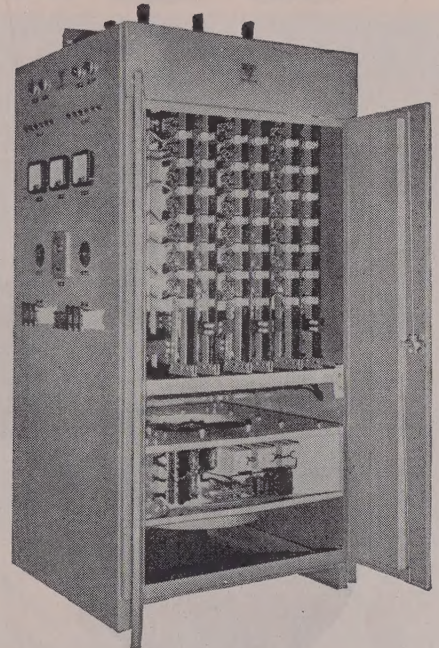*London Office:* 125 HIGH HOLBORN · LONDON W.C.1 · Tel: HOLBORN 1951-2

INDEX OF ADVERTISERS

THE TRAINING OF OVERSEA GRADUATE ENGINEERS, WITH PARTICULAR REFERENCE TO THE F.B.I. SCHOLARSHIPS SCHEME

By W. ABBOTT, C.M.G., O.B.E., Ph.D., B.Sc.(Hons.), M.I.Mech.E.

SUMMARY

The paper deals with problems arising from the training, in the engineering industry of Great Britain, of graduates from countries oversea, primarily from under-developed countries. The paper relates mainly to the Scholarships Scheme operated by the Federation of British Industries, a scheme which, though relatively small, deals with carefully selected men from a large number of countries.

The paper examines the philosophy of post-graduate practical training in the United Kingdom. It then assesses the extent of this training in industry and suggests that the total annual intake of graduates, both from home and oversea, is of the order of 5 500. The possibility of increasing this number is discussed.

The paper then considers the influence of the requirements of the major professional engineering institutions—civil, mechanical and electrical—on schemes for the practical training of graduates. After considering the types of engineer coming from oversea, the paper discusses the possible inappropriateness of British training methods for many of the visiting engineers, and suggests improvements.

The paper concludes by considering the impact of greatly increased demands which will be made upon Great Britain and other countries of the West from the emerging nations in the Commonwealth and from other developing countries.

Appendices give the balance-of-trade position with countries covered by the F.B.I. and Athlone Fellowship Schemes, and a letter from the late Sir Claude Gibb relating to the training of Canadian graduates.

(I) PHILOSOPHY OF POST-GRADUATE TRAINING IN THE UNITED KINGDOM

It has long been recognized in this country that the professional requirements of an engineer cannot wholly be provided by a university or college; but that after, or mingled with, an academic course there must be a substantial period of practical training, usually of about two years' duration. The purpose of this is not only to bring reality to theory but to give the graduate contact with people: craftsmen, technicians and supervisory staff. There have been exceptions to this requirement; where,

Dr. Abbott is Director of Studies, Federation of British Industries.

for example, scientific or mathematical brilliance indicates a career in fundamental research, an insistence on a period of practice has been assumed to be a little unrealistic.

In some other industrial European countries university courses in engineering are extended to include an element of engineering design, as distinct from theory. By this means an attempt is made to produce persons directly usable in one or other branches of engineering—in other words to produce competent specialists. The tendency in Great Britain has been to discourage too early specialization, in both theory and practice.

Most industrialized countries now offer training facilities to engineers in countries whose industries are developing, partly to give a service to these countries and partly to ensure that a knowledge of the products of the industrial nation is disseminated throughout the developing countries. Originally, the offer to the oversea men was made by enlightened manufacturing organizations in the interests of trade, but, more recently, impartial bodies and governments have intervened to bring together the technical needs of the developing countries on the one hand and the training resources of the producing countries on the other.

The training schemes which have developed in this country have naturally tended to satisfy two requirements: the needs of the home industry for qualified personnel, and the requirements specified by the professional engineering institutions for corporate membership, which, of course, can be assumed to be in the interests of the home industry. The possible inappropriateness of these requirements so far as the oversea engineer is concerned is dealt with later.

The continued popularity of British training with developing countries springs not only from our historical industrial record but also from the scale of our enterprises, which, compared with, for example, those of many American undertakings, must seem more in keeping with the immediate and more moderate aims of those countries. The extent of this training is now great and may be reaching the ultimate capacity of some firms, particularly those with mature and highly developed schemes.

(2) EXTENT OF POST-GRADUATE TRAINING IN THE UNITED KINGDOM

The number of people annually securing first degrees in all branches of engineering in British universities and colleges is about 2 600; in addition, about 1 100 secure university diplomas. Among all these is a small percentage of men from oversea. Hence the annual university crop to be absorbed in the United Kingdom by industry, consultants, research, teaching and the Services can be taken as 3 500. The great bulk of these will require practical training, to fit them to become chartered engineers.

An estimate of the total number of foreign students working in industry is about 3 000 per annum (based on work permits issued by the Ministry of Labour), and the corresponding number of Commonwealth students is certainly greater. This total, perhaps of 6 000 to 7 000, includes many who are not graduates, and the author's guess at the number of oversea engineering graduates per annum securing training in British industry is about 2 000.

This is a substantial addition to the home demand, the combined total being 5 500, and there is little doubt that many of the best known firms have as many graduate trainees as they can handle. But another approach to this question of capacity reveals a different picture.

In June, 1959, the Board of Trade issued a simply worded questionary to 560 firms concerned with the manufacture of plant and equipment, mainly engineering. The nationalized industries were included, as were all firms which had taken trainees under the various schemes sponsored by H.M. Government.*

The firms were asked to give the numbers of men from oversea who were on attachment for three months or more and receiving industrial training. Of the 560 firms approached, 258 had amongst them 2 660 trainees (1 810 Commonwealth and 850 foreign); 208 firms made a nil return and 94 made no reply.

Some of the 208 firms making nil returns said that the date was a bad one and that normally they would have had men in training.

Two conclusions may reasonably be drawn from this. First, the figure of 5 500 annually is reasonable, with the inference that the total number of graduates in training at any one time could well be twice this number, i.e. 11 000. Secondly, there is still unused training capacity in the country, not necessarily confined to the smaller firms.

(3) COUNTRIES WHICH MIGHT BE EXPECTED TO MAKE USE OF TRAINING FACILITIES IN THE UNITED KINGDOM; THE BALANCE-OF-TRADE POSITION FOR THESE COUNTRIES

The countries which might be expected to make use of our technical heritage are those which are developing power and

*Athlone Fellowships	..	..	..	..	..	..	..	B.T.
Baghdad Pact Technical Assistance Scheme (name changed to Central								
Treaty Organization Fellowships)	..	..	..	..	..	B.C.
British Council Scholarships	..	..	..	..	..	B.C.
Colombo Plan Technical Co-operation Scheme	..	..	B.C., M.L.
Colonial Development and Welfare Funds	..	..	S.O.
Federation of British Industries Overseas Scholarships	..	F.B.I.
Food and Agriculture Organization	..	..	..	B.C.
Foundation for Mutual Assistance in Africa, South of the Sahara	..	B.C.
International Atomic Energy Agency Organization	..	..	B.C.
International Civil Aviation Organization	..	..	M.T.
International Labour Organization Technical Assistance Programme	M.L.
Technical Assistance Agreement with Yugoslavia	..	..	B.C., M.L.
United Kingdom/Ghana Mutual Technical Co-operation Scheme	..	M.L.
United Nations Technical Assistance Administration	..	..	B.C.
U.N.E.S.C.O.	..	..	..	..	..	..	B.C.
World Health Organization	..	..	..	..	..	B.C.

The letters indicate the offices responsible for placings:
B.T.   Board of Trade.
B.C.   British Council.
M.L.   Ministry of Labour and National Service.
S.O.   Students Offices for Colonies.
F.B.I.   Federation of British Industries.
M.T.   Ministry of Transport and Civil Aviation.

communications, dealing with irrigation and soil conservancy problems, modernizing their city and urban services, developing their mines, and becoming industrialized. The list of countries included in the Scholarships Scheme of the Federation of British Industries (1959) is as follows:

Commonwealth	Europe	Latin America	Middle and Far East
Australia	Portugal	Argentina	Iran
Ceylon	Spain	Bolivia	Iraq
Hong Kong		Brazil	Jordan
India		Chile	Kuwait
Malaya		Colombia	Lebanon
New Zealand		Cuba	Philippines
Pakistan		Ecuador	Sudan
Rhodesia		Guatemala	Thailand
South Africa		Honduras	Turkey
West Indies		Mexico	
		Nicaragua	
		Panama	
		Peru	
		Salvador	
		Uruguay	

The Athlone Scholarship Scheme is applicable to Canada only.

It is of general interest to note the balance-of-trade position of these countries with the United Kingdom for the year 1959, which is given in Appendix 12.1.

(4) INFLUENCE OF THE MAJOR PROFESSIONAL ENGINEERING INSTITUTIONS ON THE PRACTICAL TRAINING OF GRADUATES

In their combined wisdom, the professional engineering institutions of the United Kingdom have always made the acquisition of practical training and professional experience a condition of corporate membership: academic qualifications alone have not been enough. This requirement, although well understood by British graduates, often perplexes the oversea engineer. His university qualifications usually enable him to join a national body in his own country, and he feels that he might be made at least an honorary member of British institutions while in this country. The unique character of these institutions has then to be explained to him and the importance to be attached to the term *chartered engineer*; but when it has to be admitted that many engineers in practice are not chartered engineers, and that, in fact, anyone in Great Britain can describe himself as an engineer, the visitor's mystification is complete.

While the institutions prescribe in some detail the kind of practical training which they think the graduate should have, the training actually secured may often fall short of this ideal. In so far as the training has to be fitted into production in a competitive industry, its quality depends not only upon the policy of the management but also upon the goodwill of busy foremen and work people whose interest in training cannot always be counted upon. Although, therefore, an institution may prescribe, full industrial co-operation cannot be guaranteed at all times. Doubtless the graduate applicant for corporate membership is not penalized for an adverse training background, and can expect understanding and clemency from the institution.

The Institutions of Electrical, Mechanical and Civil Engineers have set out their recommendations for the practical training of graduates in brochures which are available and which repay close study. They will be dealt with here in outline only.

(4.1) Institution of Electrical Engineers: Training of Graduates

The pattern for graduate training should extend over two years and comprise three parts:

(a) Basic workshop training: 2–4 months.
(b) General mechanical and electrical training: 8–15 months.
(c) Directed objective training: 6–12 months.

(a) is intended to give the graduate an opportunity to become familiar with the uses and limitations of machine and hand tools, to learn about the properties of engineering materials and to know something of the basic manufacturing processes.

(b) is intended to provide the opportunity for experience in fitting and assembly; inspection and testing; installation, operation and maintenance of plant; drawing-office practice; experimental or development work.

(c) requires of the graduate a choice of the type of work in which he will wish to make his career, among the following:

> Research.
> Development.
> Design and application.
> Manufacture.
> Plant commissioning.
> Operation and maintenance.
> Commercial engineering.

Having made his choice, it is intended that the graduate shall have his course carefully planned, preferably in collaboration with the head of the department in which he hopes to have a staff appointment.

The Institution's Report sets out in some detail the training as it relates to (a) a works making heavy plant; (b) a works making light equipment; (c) training in an operating organization; and (d) training in a research establishment.

(4.2) Institution of Mechanical Engineers: Report on Practical Training

The Report gives the reasons for practical training and suggests that it should be divided into two stages:

(a) Basic training: 6–9 months.
(b) Secondary training: 15–18 months.

The reasons for practical training are that the graduate aspiring to corporate membership should have direct practical knowledge of:

(i) The potentialities and limitations of basic workshop processes.
(ii) The abilities and skills required by personnel employed in these processes.
(iii) The important part played by experience.
(iv) The importance of co-operation and good human relations in promoting efficiency and well-being on the shop floor and in the office.
(v) Some of the principles of engineering organization and administration.
(vi) Various general aspects of work undertaken by professional engineers.

The objects of the basic training are to provide practical knowledge of the use and limitations of the basic workshop processes with hand and machine tools, to gain an appreciation of the range of skills and experience of the personnel engaged in engineering workshops, and to learn about the basic manufacturing processes.

The secondary training has to be related to the graduate's ultimate sphere of employment, from among:

> Manufacture.
> Design and development.
> Commercial departments.
> Operation and maintenance.
> Research.

The Report gives recommended schemes of training at the secondary stage which fit the graduate for future employment in one or other of the above branches. Examples are given of actual items of work which the graduate should carry out.

(4.3) Institution of Civil Engineers: Practical Training

The Institution of Civil Engineers has placed the responsibility for the practical training of their future members squarely on the shoulders of practising chartered civil engineers who are expected willingly to accept this responsibility. This has been forcefully stated by a Past-President, Professor A. J. Sutton Pippard, in the following terms:

> The most important function of practical training is the amplification of theory by experience; and it is one of the most urgent and responsible duties of the established engineer to deal faithfully with the young men who will ultimately succeed him and who must rely on him for the widening of outlook which will make possible the full use of the scientific education they have received.

An Index of Engineers willing and able to provide training is prepared under the authority of the Council of the Institution. Engineers on this Index accept the conditions laid down by the Institution and give training under a prescribed form of agreement extending over 2 or 3 years, the duration depending upon the academic qualifications of the trainee. One year is to be spent in an engineer's office and one year upon engineering works.

After training there comes the professional interview, at the Institution, for which the candidate for membership submits a report giving an account of his training and experience, and, with this report, drawings, calculations and quantities relating to his ordinary work during training.*

Every drawing, bill of quantities and note of calculations has to be signed by the candidate's sponsor, who must be in a responsible position as an employer or principal. The interviewers are representatives of the Council of the Institution and are selected for their knowledge of the particular branch of engineering in which the candidate has been engaged. The interviewers question the candidate to ascertain his competence and the degree of responsibility held by him. At the conclusion of the interview the candidate is required to write an essay which may involve, in part, a specification.

(5) NUMBERS OF UNIVERSITY GRADUATES ACCEPTED ANNUALLY FOR ASSOCIATE MEMBERSHIP

The loads falling upon the three major institutions in their assessment of claims from university graduates for election are indicated by the following figures, which relate to *acceptances* for the year 1959:

	I.C.E.	I.Mech.E.	I.E.E.	Total
Candidates with degrees in engineering or science, successfully claiming election to associate membership.	464	400 (estimated)	456	1 320

This total of 1 320 relates to men who graduated at their universities five or six years earlier; and it may be assumed that the current larger output of the universities and colleges (3 500 in 1959, see Section 2) will bring about a corresponding increase in the numbers applying for associate membership.

These numbers have a bearing on the comments in Section 7.

(6) TYPES OF OVERSEA GRADUATE TRAINEES

There are two main types of engineer who may wish to secure training in the United Kingdom: the young graduate with little or no practical experience, and the mature engineer with considerable experience who requires up-to-date information which will be directly useful to him in furthering his career. The F.B.I. Scholarships Scheme (and the Athlone Fellowships Scheme) make awards in both categories. Because of their very different requirements they will be treated separately.

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* These drawings and papers need not be confined to civil engineering in its narrow sense, but may be concerned with mechanical, electrical or chemical engineering, town planning, gas engineering, petroleum refining and other fields of engineering activity.

(6.1) Newly Graduated Engineer

In the main branches of engineering, civil, mechanical and electrical, established training schemes are available and are suitable for a fair proportion of oversea men, particularly in civil engineering. But for many the existing schemes leave much to be desired, and the deficiencies are discussed in Section 7. Too often the graduate is regarded as an apprentice; his training is controlled by the apprentice supervisor and the emphasis is on the acquisition of craft skills. In many production shops the graduate cannot participate in operations, either because of labour production arrangements or because of trade-union opposition; he can only observe, and boredom results unless special precautions are taken.

In some branches of engineering graduate training has not been fully developed and the oversea man is unacceptable. This is largely true at present in chemical engineering, which is a branch of the greatest importance in many developing countries.

(6.2) Mature and Experienced Engineer

The requirements of the mature and experienced engineer are always particular; the engineer has been in practice for several years and is committed to a career in the chosen branch of his profession. He comes to us for specialist knowledge or modern practice which he cannot secure in his own country. He can only be treated on the basis of a visiting engineer to receive exceptional treatment from those firms which will accept him. Unless these conditions obtain, it is better for the man not to come.

The experience of the F.B.I. in the handling of such cases has been almost uniformly agreeable. The period of the scholarship has usually been between 6 and 12 months. Where manufacturing experience is required, it has often been necessary to attach the engineer to a number of firms, often as many as 12 to 15, and the labour involved in the arrangement is excessive. Nevertheless, the trainee has invariably left with a good knowledge of the range and variety of the equipment in which he is interested, and this cannot but be to the advantage of both countries. It is probable that more satisfaction results generally, both to the scholar and to the receiving firm, from this kind of attachment, than from the normal two-year period.

(7) SUITABILITY OR OTHERWISE OF THE NORMAL BRITISH SCHEME FOR THE YOUNGER OVERSEA GRADUATE

Most oversea engineers are expected to assume responsibility in their own countries at an earlier age than their British counterparts. Moreover, engineers in most developing countries are scarce and often have to cover more than one branch of engineering; for example, such an engineer may be called upon to give advice on all aspects of hydro-electric power and not to be narrowly mechanical, electrical or civil.

Again, engineers from foreign countries are not usually interested in becoming members of British institutions, language often being the main deterrent, and while they fully appreciate the purpose of the schemes of training laid down by the institutions, they feel that their own requirements are not met.

Dealing first with engineers concerned with industrial products, the common complaint of the oversea man, particularly from an under-developed country, is that he is required to conform to training which all too often will fit him to be a *producer*, whereas he will not be called upon to produce—in his foreseeable future. He will rather purchase, install, operate and maintain. He resents spending long periods in fitting and machining, which he regards as a waste of precious time. He is not interested in becoming the 'complete engineer', in our understanding of the term. He does not really believe that

some experience of repetitive work is good for the engineer w will later call upon others to do much repetitive work, nor do he always accept the argument that it is good for him to m with work people. Again, he would prefer not to stay with o firm, however comprehensive its operations, but to spend ti with several and thus gain knowledge of a wider range British manufactures. It is of interest that this kind of view held officially by a Commonwealth country, which asks that young engineers should spend training periods with a numb of named firms that produce equipment of particular importan to the country. Provided that the training arrangements not degenerate into a kind of buyer's tour, there are good co mercial reasons for giving the foreign graduate a survey of industrial potential; and many oversea engineers might be ve satisfied with experience in the office of a mechanical or electri engineering consultant, coupled with periods spent in organiz tions concerned with the planning, equipping and services factories—although there are few of such firms. Indeed, t suggestion has been made that some of the oversea mechani and electrical men should be treated rather in the way we d with the civil engineer, who is not required to undertake cr operations such as laying bricks or mixing concrete, and who position is more 'professional' throughout.

Again, the young oversea graduate is always anxious to secu information, but he finds that his questions can usually directed only to those who cannot answer them. It is rare f him to receive help from the professional engineers in ma manufacturing organizations; he does not meet them, and th are much too involved in their own problems to feel free to h the young foreigner. This situation does not often arise civil engineering simply because the graduate is not attached the craftsmen for his experience. But it arises invariably in t other branches and it is the burden of a steady stream criticism from trainees. If management believes that it is go policy to receive into their works for training selected men fro other countries who are destined to become industrial lead in those countries, it would appear that management shou give much more attention to this particular question of t acquisition of knowledge; otherwise the outcome of the graduat stay with us will not always enhance our national engineeri reputation.

This belief was held by the late Sir Claude Gibb, who, when was Chairman of the Athlone Fellowship Committee, address a letter to selected directors of firms urging a new approach. copy of this important letter is given in Appendix 14.2.

A factor in the industrial situation is the presence of lar numbers of apprentices in the works, many of whom w achieve professional status by qualifications obtained in techni colleges. The oversea graduate regards himself as superior the senior apprentices, often without very good reason, a assumes that his treatment should be different. It is und standable that this situation, not fully appreciated by t oversea graduate, can give rise to many difficulties.

Coming now to the civil engineer, the common request for a mixed experience, preferably for block periods, on roa and bridges; dams; structures; drainage and water supply, Common also are requests for both consultant and contract experience and for specialized training—at present, experien in prestressed concrete is the fashionable demand. It extremely difficult to persuade the keen oversea graduate accept the argument that short periods on various speciali work cannot be arranged, and, moreover, are not in his b interest. It is of little use telling him that civil engineering very much an attitude of mind and that the kind of work undertakes hardly matters. He is anxious to get experience obtainable at home; and he does not want to have too m

drawing-board work—that stop gap which the employer uses while assessing the graduate's worth and reliability.

But students from certain countries find the civil-engineering training here most satisfactory. They have stated that, in their own countries, employment after graduation does not give them much engineering experience but rather causes them to function as technical clerks. The disciplines involved in the training here—in having to deal thoroughly with a job and to detail it on the drawing board—have given these men an assurance and outlook whose value they fully appreciate.

(8) FINANCIAL BASES OF ANY TRAINING SCHEME

The principal costs which arise from the training of the oversea graduate relate to (a) his journey to and from the United Kingdom, (b) his subsistence during the period of training, (c) his journeys within the United Kingdom, and (d) his training in industry.

(a) The average cost of F.B.I. scholars' journeys to and from the United Kingdom is £220. Concession rates are used wherever possible.

(b) The rate of subsistence should be such as neither to lower nor raise the graduate's standard of living very much. A difficulty arises here; if British living standards are higher than those in many countries they are lower than those in some. As differential scales are highly undesirable, a compromise has to be adopted. Current subsistence allowances for the Athlone and F.B.I. Schemes are £476 per annum for the young graduate and £550 for the maturer engineer, both tax free. These are by no means liberal, and they are really insufficient, alone, to attract men from countries able to offer very high starting salaries to graduate engineers, e.g. Venezuela.

(c) The cost of necessary journeys within the United Kingdom, including approved visits to works, is of the order of £40 per scholar in the F.B.I. Scheme.

(d) The cost of the training within industry is very difficult to assess or measure. Assuming that the employment is unproductive, and assuming a well-organized training machine, the cost to the firm per annum has been given as £500. It could well be more. However, if the trainee is so useful a person that he could play a part in research or development, then clearly the net cost to the firm would be smaller and could be nil. Again, a competent graduate in a consultant's office is not likely to be much of a financial burden upon the firm.

The allocation of these charges in the F.B.I. Scheme is as follows:

(a) Cost of external journeys, which is met by grants from H.M. Government, or, for certain types, by the scholar himself.

(b) Subsistence, which is met by the organization receiving the trainee.* There are exceptions to this. For example, municipalities can make no payment from the rates in respect of trainees; certain of the nationalized industries will make no payment; some firms will not pay the full subsistence charge; and firms receiving a trainee for a period of less than three weeks are not asked to make any payment. The subsistence in these cases is met partly by grants from H.M. Government, and partly by financial assistance given to the Scheme by firms not able themselves to provide training.

(c) Cost of internal journeys, which is met by grants from H.M. Government.

The financial assistance given by firms interested in the Scheme but unable to take scholars is also used to cover the

* It should be said that a firm's expenditure under this head is recognized as an 'allowable expense' by the Inland Revenue Department.

cost of subsistence while scholars are unattached and to meet to some extent the costs of administration. This financial aid is invaluable and essential to the solvency of the F.B.I. Scheme.

(9) IMPACT ON OVERSEA GRADUATES OF LIFE IN GREAT BRITAIN

No account of the training of young, intelligent and impressionable men from countries oversea would be complete without a section on their personal reactions; and the following account is the result of many talks extending over ten years with young men from a wide variety of countries.

Among the things British which impress the oversea graduate are many that we either forget about or take for granted: the excellence and cheapness of our travel facilities; the reliability of our postal services; the kindness of ordinary people; the discipline or common sense exhibited by, for example, bus queues. Other features are criticized; for example, the dull life in any of the smaller manufacturing towns—insufferably dull to a Latin American from a city where life begins at 11.0 p.m.; an impatience with our obsession by past traditions and customs; the ignorance of our people concerning the trainee's own country; the deficiencies of lodgings. Differing conditions oversea leads one graduate to say that in Great Britain there are no poor, whereas another will say that our general standard of life is low.

Prejudices against colour are often reported. Cultured scholars from ancient races have been humiliated by ignorant landladies or hotel proprietors, and by foremen and workpeople. The greatest difficulties always arise where the scholar's command of the English language is deficient, and also where the scholar has little sense of humour. The F.B.I. takes considerable care to ensure that the scholar is cushioned as far as possible against the adverse effect of prejudice and ignorance; but it is nevertheless possible for the effect of an excellent technical training to be offset by influences beyond the control of any scheme or organization, to such an extent that the scholar may become anti-British.

The problem of the married scholar who wishes to bring his wife with him—and possibly children, too—is an extremely difficult one. On the one hand there is the depressing effect on some scholars of severance from a closely knit family. This effect, in the cases of several F.B.I. scholars, became quite unbearable to the point of melancholia. On the other hand there is the handicap to mobility of the presence of a wife and children and the sickening effects of colour prejudice where this arises. Although on balance it would appear that scholars should be discouraged from bringing their wives with them, it is impossible to make this a general rule. Each case differs from the next, and all that can be done is to make sure that the scholar is fully aware of the difficulties and dangers.

The continuing comment of almost all F.B.I. scholars who are mechanical or electrical engineers is that they rarely meet the firm's professional engineers socially. This is largely because they never meet in the works; they are unknown to one another. The oversea graduate feels this neglect acutely because, he says, it would never happen in his own country.

A different relationship often obtains among the civil engineers, many of whom report much individual kindness from their employers, such as shared holidays and sports.

The professional engineering institutions kindly invite F.B.I. scholars to their meetings, at which the scholars do have the opportunity of meeting professional engineers—a privilege which is greatly appreciated.

The assistance and wisdom of the British Council are always forthcoming when social problems of the F.B.I. scholars can be ameliorated by the Council's aid; and the Institutions of Civil, Mechanical and Electrical Engineers and their Centres

show a continuous interest in the welfare of all oversea engineers and do much to make their stay in Britain pleasant and profitable.

The general impression conveyed by F.B.I. scholars is that their stay amongst us has been enjoyed and that it has been well worth while. They regard us as a mature and orderly, if unexciting, people; but they seem to find our way of life slowly more and more acceptable—some scholars have no strong wish to return home and a few who came for two years have stayed for four. They appreciate the cultural resources of Great Britain, and particularly of London—which is always the magnet; they find amusement in our habits and customs—the Englishman's loquacity in a pub and silence in a train. Usually the firebrand after a six months' stay is a very understanding person after two years.

(10) POSSIBLE FUTURE DEVELOPMENTS

(10.1) H.M. Government

Many training schemes are sponsored by H.M. Government, the extent of state aid varying between them. It is understandable in schemes such as the Athlone Fellowships and F.B.I. Scholarships, which are not altogether altruistic, that the state should expect industry to bear the major cost of training—this can, of course, attract tax relief; and the argument is particularly appropriate in the case of countries such as Canada and Australia, which, while not fully developed, are themselves giving great aid to under-developed countries.

But for many truly under-developed countries, action—financial and technical—on an international scale is being pressed upon the free countries of the West; it being held that the acceptance of nothing short of an enormous industrial training programme will meet the world situation. Such a programme would seem to involve the creation here of training schemes in numerous smaller firms unaccustomed to such activities, and, clearly, reliance upon their acquiescence and acceptance of the high cost would not be reasonable.

Two essential elements for a thorough assessment of the national situation are at present missing. These are:

(*a*) The full extent of the training load now falling on British industry.

(*b*) The extent of the surplus capacity which can be made available.

At present industry is being asked by a quite large number of people, independently, to accept trainees; and the acceptance by the right firms of the most appropriate trainees, to ensure a fair spread, is haphazard. Probably close planning is not possible, but information on (*a*) and (*b*) would greatly help all the sponsoring bodies. An answer to (*b*) will vary with the extent of Government aid; if no aid is forthcoming, some smaller firms may be unable fully to co-operate.

(10.2) Professional Engineering Institutions, and Industrial Training

The difficulties confronting the engineering institutions in their attempts at ensuring satisfactory training for our own graduates—the professional engineers of the future—are well known and probably not capable of a speedy solution. The size of the problem is reflected from the figures in Section 5.

Competitive industry will always be moved to place economic production and solvency first; and any costly activity which tends to imperil these will be relegated to second place, even though the benefits to industry and the nation are recognized. In these circumstances the institutions have to rely upon industrial goodwill and a sense of responsibility among corporate members in industry, which can be effective only among firms with enlightened managements.

If the Institutions of Mechanical and Electrical Engineers regarded the matter as primarily their concern, they could prepare and publish a list of approved firms with which a graduate could secure a sound training under the general guidance of competent professional engineers. This would cause the young graduate to try to avoid those firms which were not on the approved list.

However, such a scheme would be likely to break down in several ways. First, the Institutions would not wish to make comparisons and draw distinctions among hundreds of firms, nor is it likely that they could undertake the work of assessment which this would involve; secondly, the Institution members in the firms would often be disinclined to associate themselves with training unless they were specifically charged with that duty; and thirdly, many graduates would always have to get what training they could, and they would not be always excluded from consideration by the Institution because this happened to be with a firm not on the approved list.

The foregoing are the difficulties arising with the training of the home graduate. They are intensified with the training of the oversea graduate whose requirements are so often unusual and whose training can be so costly. For these reasons it would not be unreasonable for less affluent firms to take the view that they cannot do this job effectively unless they are assisted financially; for example, in engaging the services of professional engineers whose responsibilities would be confined to the training of oversea graduates. This would remove the training activity from the arena of competitive production and would enable it to continue without much reference to the fluctuations of business. Many large firms do appoint engineers of the quality suggested, who are concerned jointly with recruitment and training; but smaller firms cannot afford such appointments and can deal satisfactorily with the training problem only if the directors take an interest and see that the man gets the training he needs.

(10.3) Sponsoring Authorities

The sponsoring authorities should always keep in mind the relative size of their schemes. For example, the F.B.I. Scheme deals with about 75 new scholars a year and the Athlone Fellowship Scheme with about 42. Both are marginal when compared with the total numbers of graduate engineers accepted by firms every year. They are, however, important in that they deal with men who are thought to have the quality of leadership and who will be important figures in the future in their own countries.

Again, a particular feature of these Schemes is the subsequent action taken when the scholar has returned home. He is kept informed of engineering developments, is encouraged to found or join an association of old scholars, and is supplied with technical and general assistance whenever he requires this.

All sponsoring authorities have a good deal of information about firms, culled from the reports of scholars or arising from specific difficulties.

It is probably true that firms vary, as regards their suitability for training, with the personnel available from time to time; but an accumulation of adverse comment would cause a sponsoring authority to avoid a certain firm if a better alternative were available. It is probably true that a mild process of weeding out is, in fact, operative.

(11) ACKNOWLEDGMENTS

The enlightened attitude which many firms have taken on the training of graduates is a matter for national satisfaction. These

rms have over the years, by trial and experiment, evolved chemes which are near perfect, and which certainly fully meet he requirements of the professional engineering institutions. here is thus in the country an accumulation of knowledge hich doubtless may be made available to other firms.

The author wishes to make full acknowledgment of his ndebtedness to many education and training officers in these ioneer firms, whose experience and advice have been freely laced at his disposal.

Much help has also been provided by officers in the Board f Trade, the British Council, and the three major engineering nstitutions; and also by colleagues in the Federation of British ndustries.

All those consulted have not only an appreciation of the roblems to be solved but a belief in the country's capacity to olve them.

(12) APPENDICES

(12.1) United Kingdom Trade Year, 1959

		Imports by United Kingdom (c.i.f.)	Total exports from United Kingdom (f.o.b.)	Balance
		£ million	£ million	£ million
Australia	.. ..	222·9	225·3	+ 2·4
Canada	.. ..	312·3	213·4	− 98·9
Ceylon	..	40·0	31·9	− 8·1
Hong Kong	..	33·5	35·6	+ 2·1
India	.. ..	142·6	172·6	+ 29·9
Malaya	..	35·6	31·2	− 4·4
New Zealand	..	183·1	97·5	− 85·6
Pakistan	.. ..	25·8	34·6	+ 8·9
Rhodesia	..	90·3	49·6	− 40·7
South Africa	..	89·2	150·8	+ 61·6
*West Indies	..	68·1	60·6	− 7·5
Portugal	.. ..	14·8	21·3	+ 6·5
Spain	.. ..	36·1	21·2	− 15·0
Argentina	.. ..	105·5	40·4	− 65·1
Bolivia	.. ..	13·6	0·9	− 12·7
Brazil	.. ..	37·3	13·6	− 23·6
Chile	.. ..	26·3	6·6	− 19·7
Colombia	.. ..	11·7	6·1	− 5·6
Cuba	.. ..	10·2	15·3	+ 5·1
Ecuador	.. ..	0·3	2·1	+ 1·8
Guatemala	..	0·6	2·0	+ 1·4
Honduras	..	0·4	0·7	+ 0·3
Mexico	.. ..	7·1	13·7	+ 6·6
Nicaragua	..	1·1	0·8	− 0·3
Panama	..	0·5	3·4	+ 2·9
Peru	.. ..	14·4	6·2	− 8·2
El Salvador	..	0·8	1·2	+ 0·4
Uruguay	..	6·0	3·5	− 2·6
Ethiopia	.. ..	1·5	2·7	+ 1·1
Iran	.. .. ..	57·2	38·5	− 18·7
Iraq	.. ..	52·8	31·9	− 20·9
Jordan	.. ..	0·1	5·8	+ 5·7
Kuwait	.. ..	126·0	18·3	−107·6
Lebanon	..	2·4	9·7	+ 7·4
Philippines	..	3·4	7·8	+ 4·4
Sudan	.. ..	18·6	13·0	− 5·6
Thailand	..	2·0	12·6	+ 10·6
Turkey	..	14·3	16·1	+ 1·8

* Jamaica, Leeward Islands, Windward Islands, Barbados and Trinidad and obago.

Source: Accounts relating to the trade and navigation of the United Kingdom December, 1959).

(12.2) Letter from the Late Sir Claude Gibb

ear

I am writing as Chairman of the Managing Committee of the thlone Fellowship Scheme to consult you regarding the kind of raining which United Kingdom firms should be prepared to offer to the young Canadian engineers who come over here for two years post-graduate training, either in industry or in a university or one year in each.

You are, I am sure, aware that the object of the scheme is to impress these young men with the achievements of the United Kingdom engineering industry in research, development, design and production, so that when they attain really responsible positions in Canada they will be favourably disposed towards United Kingdom engineering products.

The Scheme has now been running for eight years and some 230 Fellows have completed their training, while some 75 are at present over here.

United Kingdom firms have cordially welcomed Athlone Fellows into their establishments and there has been no difficulty in placing those who have asked for all or part of their experience to be in industry.

The majority of Fellows have, however, asked to spend at least part of their Fellowship in universities and the Committee are concerned that only some 40% of 'man years' have been, or will be, spent in industry and 60% in universities.

There are many reasons for this:

(i) The applicants for Fellowships invariably come from the 'top layer' of the graduate class and are therefore comparable with those members of United Kingdom graduate classes who would be invited by their professors to stay on at the university for research or study for higher degrees.

(ii) Canadian employers place a great deal of weight on higher degrees, i.e. M.Sc. or Ph.D., whether the individual is likely to be employed on design or on production and not necessarily on research or development work.

(iii) There is practically no apprenticeship in Canada and therefore no tradition of obtaining works experience—except vacation employment—before attaining professional status.

The Managing Committee are satisfied that both graduate courses and research work in the engineering departments of our universities and research establishments do give the Fellows an insight into the latest engineering research work, and very frequently intimate contact with industrial firms.

The Committee would, however, like to see a higher proportion of these young Canadian engineers spend the major part of their Fellowship in industry. They are not prepared to put pressure on a successful candidate to do so, since they believe he will carry away a much better impression if he is given the type of training which he and his advisers in Canada think most advantageous to him and to Canadian industry. Nor do the Committee think that any strong preference should be given during the selection procedure to men who opt for industrial training. The important thing is to select the men who are likely to obtain high executive positions in Canadian industry and then to satisfy them that the experience they are to be given under the Scheme is the most suitable.

If then more Fellows are to be attracted to industrial experience as opposed to university work, we must ensure that the industrial training in the United Kingdom is really attractive to the young Canadian engineer, bearing in mind his background and his own knowledge of the needs and desires of Canadian industry. This frequently means that the Canadian engineering graduate is not at all impressed by the United Kingdom 'graduate apprenticeship course' of two years, which in most cases has been organized by United Kingdom industry in consultation with the professional institutions concerned and is primarily designed to meet the detailed requirements of the institutions for corporate membership.

We find that the Canadian graduate is anxious to be given work involving some responsibility and use of what he has learnt in his undergraduate course. He is not concerned with acquiring a craft skill or even knowledge of an engineering craft, since the organization of the engineering, and particularly the light engineering industry in North America, does not expect this type of skill or knowledge from the professional engineer.

A number of engineering firms in the United Kingdom have realized the rather special needs of these young men and have, in fact, provided exactly the type of experience which they desire. There is no doubt that the policy of these firms has been greatly appreciated and will in due course pay handsome dividends.

As Chairman of the Athlone Fellowship Managing Committee in the United Kingdom, I should like to be able to offer to Athlone Fellows, on behalf of United Kingdom engineering firms generally, a promise that their individual wishes will be met as nearly as possible. Thus whenever possible they will be given work of some responsibility, e.g. as assistant to a middle executive, an assistant works manager, or work in the design office, production planning office, testing bay, etc., rather than be expected to work at a bench or machine tool, unless the Fellow expresses a wish to do so.

I hope that it is quite clear that nothing I have said above is intended to be in any way a criticism of any graduate apprenticeship scheme operated by any organization in this country.

What I wish to do is to tempt a higher proportion of Athlone Fellows to take the major part of their Fellowship in industry rather than in a university, and to this end to make experience in United Kingdom industry attractive to them in view of their rather special needs and wishes, which are due to differences between both the industrial and educational systems in North America compared with those in the United Kingdom.

I shall be very glad indeed to have your comments on this matter as soon as possible as the information will have considerable bearing on the advice and instructions which will be given to the individuals and committees responsible for the selection of the 1959 group of Athlone Fellows. This selection will take place between the middle of January and end of February, 1959.

Yours sincerely,

13th October, 1958.   (Signed) CLAUDE GIBB.

DISCUSSION BEFORE A JOINT MEETING OF THE INSTITUTION WITH THE INSTITUTION OF CIVIL ENGINEERS AND THE INSTITUTION OF MECHANICAL ENGINEERS, 3RD NOVEMBER, 1960

Sir Herbert Manzoni: The author has pointed out that in civil engineering it so happens that there is an insistence on the personal responsibility of the trainees' mentors. The Institution of Civil Engineers compiles a register of people they will allow to take trainees, making them personally responsible. They have to submit not only an outline of the training that they will give but a record of the training given at the end of the period. This may be difficult in mechanical or electrical engineering, but at least it works with civil-engineering students.

I am very interested in the author's remarks about the reactions of the students to doing manual work, or rather repetitive operations. In every branch of engineering there is a certain amount of repetitive and monotonous work, and this is certainly so in civil engineering. I agree entirely that these students are at a creative age. It has been said that almost all creative work is done by men under the age of 35, which is perhaps a little older than the age that the author has in mind. There may be a good deal of truth in that; but, even so, I have always thought that it is as well to impress the student with the fact that there is a certain amount of work in any profession which must necessarily be monotonous. When I was a student, in my own time at week-ends I went out on to jobs in order that I might be able to lay bricks and do some of the manual craft work of the men whom I was later to control. What is interesting is that I wanted to do that; I did not need to do it. Have students changed so much that they reject some of these manual operations, or do they get too much of them?

Mr. S. E. Goodall: In March, 1960, I was invited by the author to attend the annual reunion of the F.B.I. scholars, and had an opportunity to talk to those of the scholars who were electrically minded. They were extremely frank, and I can support what the author has said about their reactions, apart from the fact that he has been too polite. Many of the remarks made to me were very pungent and very much to the point.

Many of the larger companies and firms represented here have very well-established and well-run education departments. The complaint which I received, however, from these oversea graduates was this. They say, 'When we arrive we are ushered into the education department and have a talk with the officer in charge, but we then go on to a job, and until we again see someone from the education department, nobody takes a very lively interest in us, nor is it possible for us readily to discuss our personal position and problems with men whom we regard as professional engineers, men actually doing the job in development and design offices'.

This is a real difficulty. It is easy to tell these young men that they should ask for help from the men they have in mind, but some of these young men have language difficulties when they arrive and naturally they are diffident about making such an approach. I would make an appeal, in particular to the younger members of The Institution of Electrical Engineers—and I think that this applies equally to the younger members of the other Institutions—to go out of their way as individual and responsible professional men to ensure that, if there are within

their range any of these young men from abroad, they will make personal contact with them and do their best to supplement the help and advice that the young men receive from the education department. This would be a constructive action of great value. To our shame, we have to face the fact that we do not take the trouble to do this.

The author is not quite up to date with regard to the training requirement regulations of The Institution of Electrical Engineers. I refer to the fact that once more we are following the example of our colleagues in The Institution of Civil Engineers and are recognizing, as an alternative to the more stereotyped form of practical training, training under the direct sponsorship of one of our corporate members. This may well be the pattern of the future, and I would again emphasize the responsibility which we all have as professional engineers for these young men. This applies equally to our own graduates from British universities, but I am not concerned with them at the moment. There is now available, as an alternative to the regular system, which is by tradition a two-year postgraduate training, an equivalent period under the direct charge and sponsorship of a corporate member. As individual professional men we must accept this responsibility for this. It is no use expecting the managing director and the managers of departments, many of whom are not engineers, to accept this responsibility or appreciate what is involved.

Various other and less important points were made to me when I met these young men. One was the complaint that they had not sufficient money to obtain English textbooks. Careful thought should be given to this, because to restrict these young men from oversea in this way, so that they have not enough money to obtain textbooks, and even the publications issued by our own companies, is, to say the least, absurd. I believe that the F.B.I. find some difficulty in this respect. They are now providing a great deal of money for this scheme. If they have difficulty, it is for us in our industrial organizations to try to help. We offer library facilities to these men, and I believe that the library facilities of The Institution of Electrical Engineers are open to them also, but that is not quite the same thing. These young men should be able to go home with some really good books in their possession, written in English and dealing with English practice. What better form of propaganda could we have?

Mr. C. H. Waldram: We have had a number of F.B.I. scholars, and it may be of interest to describe some of our reactions. It is unlikely that we shall derive much benefit from taking these men, for most of them have come from countries in which we have no special interest, but the scheme is beneficial nationally, and we are glad to participate. Of the two types of scholar available we much prefer the young graduate who fits readily into our training programme, but so far only one man of this type has been submitted. This is not a criticism of the author's organization, for it is appreciated that it may place the men accepted for training.

We have noticed a tendency for scholars to want to move

apidly from one type of experience to another during their period of training. This may be appropriate for the experienced ngineer who wishes to make a rapid survey of differing types of plant with a view to purchase, but I would not consider it appropriate for the young graduate. In my view it is an essential part of training that he should be integrated in the organization in such a way that he is doing a useful and productive job. It is of little benefit to the man or the organization if he spends his time as a watcher rather than a doer.

Our own graduate trainees may spend two years or more on civil-engineering and building sites before starting on design work, and a large part of their function is concerned with ensuring accuracy of construction in accordance with design data. The technical content of this work is not very demanding to a graduate, but the essential factor is that he is an integral part of the site organization, and in a position to learn how the industry tackles a wide variety of construction and organization problems.

Mr. C. G. Bevan (*Rhodesia*): The training of graduates by the consulting civil-engineering firms has been upheld as the most enlightened of all branches of engineering. If, as has been suggested, their example should be followed by others, the system deserves further investigation.

Unfortunately, discussion with trainee graduates (whether local or oversea) now working with consultants, reveals that two out of three are by no means happy; their main complaint is acute boredom. Their engineering experience has been confined to routine detailing work which many consultants apparently consider adequate training. Even in firms that do not hold this view, bad personnel management, a shortage of draughtsmen, and a lack of suitable work can still produce these unsatisfactory conditions.

These facts, and the fact that consultants are in business, are of vital importance to the whole present concept of training, as The Institution of Civil Engineers places this responsibility almost entirely on the consultants themselves. This may have been a mistake. In spite of the undoubted integrity of most consultants, it is quite apparent that many cannot honour their obligations at all.

It seems that the position of the graduate urgently needs clarification. Is he a qualified man with the potential to take responsibility, or is he just another human draughting machine? It is for The Institution of Civil Engineers to define the status of the graduate engineer and the sort of work he is entitled to while under training. This should help to exclude those firms which cannot guarantee instructive work.

If the training period is to have any significance in terms of real value, greater control seems unavoidable. Perhaps it would be better if the other engineering institutions took their lead from the professions of law and medicine, where development of responsibility is closely controlled.

Mr. R. G. Bellamy: We must now have had 30 or 40 F.B.I. scholars in the supply industry.

Not less than 1 000 people, from 66 different countries, ranging from craftsmen to graduates have spent time training in the industry in the last ten years. It has been no small job giving these people the training they are seeking, and each presents us with an individual problem. But they have certain things in common. Despite agreeing on a programme of training when they arrive, all have a very healthy desire to vary that programme in the light of what they see around them. They have an inexhaustible energy to probe, examine and analyse, and they desire to know British people and to learn something of the country.

The author made some complimentary remarks about electricity supply training, but I can assure you that we meet many

of the difficulties he has outlined. Where the training is a success I have no doubt that it is because of the enthusiasm of the individuals these men meet. Where it is a failure it is invariably due to the rigidity of the programme, and here I think that the Institutions have some responsibility in their tendency to develop in the minds of those responsible for training in industry the programme approach. My feeling is in the other direction. I agree with the new I.E.E. pamphlet on the training of graduates, which states that: 'It should be the aim of training to develop in the man a flexibility of mind, a readiness to question traditional practices and to vary them by using new techniques.'

One other type of trainee that we increasingly meet is the man who is sent to this country not to be trained but to be fully employed for a period in order to gain experience of British practices. This seems to me a challenge which this country must meet. It means possibly accepting the man on a training basis for an initial period of, say, two months, and in that time assessing his abilities with a view to placing him in a suitable post.

Mr. M. Krikler (*Peru*): I am very glad to find that many of you understand the point of view of the F.B.I. scholar. We do not come here to lose time; we come to learn as much as we can in the very short time of two years, and also about England and its very old culture.

We do not want to spend a long time in the workshops acting as cheap labour; we have come here for something better. We can be used in more productive ways, and given the opportunity there is much that we can do.

English people are very polite, but they are also very reserved. I have found many times that they do not want to ask personal questions, which may be necessary if we are to be understood, and it is important that we should be understood in order to be useful to the company. We want to learn by our mistakes, and we want to know why things we do are wrong. It is important for us to have that opportunity.

We are here for only a short time, and we have to get the best experience we can.

Mr. R. F. Marshall: In recent years my company has had 16 F.B.I. scholars. This represents about 8% of the oversea men in training during the same period. Of the 16 only five stayed for two years, two came for a year, and the remainder for periods of only a few months.

I believe that some of the defects in the F.B.I. Scholarship scheme mentioned by the author—e.g. the lack of social contacts, and the absence of contact with technical and scientific staff—stem from the pattern of the courses prescribed by the F.B.I., which have already been described as 'butterfly' training, namely rapid movement from point to point. I suggest that the training arrangements which were introduced for oversea men in the electrical industry some 40–50 years ago were and have been successful because the trainee has been associated with one employer and has been trained largely in one locality. These conditions permit both social and technical contacts. A trainee who can only stay for two months can hardly be expected to make effective social and technical contacts in this short period of time. I suggest that the F.B.I. should review their training policy.

During a visit which I paid to Canada last year I had the opportunity of visiting eight universities where I met the members of the local selection committees concerned with Athlone Scholarships. These discussions confirmed that the Canadian graduate usually prefers the Athlone Scholarship to an industrial oversea scholarship, because the former can be wholly or partly devoted to university work, which in a number of cases will lead to the award of a further, but not necessarily higher,

qualification. The Canadian graduate loves a 'label', but if the Athlone Scholarship scheme is to be fully effective I suggest that more Canadian graduates should be encouraged to devote the whole of the training period to gaining industrial experience. There appears to be little or no follow-up of Athlone scholars when they return to Canada. This compares unfavourably with the arrangements already developed with regard to the F.B.I. scholars.

Mr. J. M. Stock (*Uganda*): In the list of countries included in the F.B.I. Scholarship scheme and set out in Section 3 of the paper, there are some omissions which seem to me to be important and remarkable. I refer to the countries of East and West Africa. These are under-developed and emergent territories with a combined population greater than that of Great Britain, with an area very many times as big, and with immense possibilities. East Africa alone imported goods from the United Kingdom in 1959 exceeding £45 million in value. They will have an enormous potential demand for engineering products in the future. The future chief engineers and senior executives of these countries, especially East Africa, are now or about to be in training. Great Britain is now in a very favourable position, but if the opportunity is not grasped to get as many as possible of these young engineers sympathetic towards this country and interested in its products now, others will do so.

My further comments refer particularly to East Africa, where, for the past 11 years, I have been intimately concerned with technical education and training. The Royal Technical College of East Africa was opened four or five years ago by H.R.H. Princess Margaret, with a faculty of engineering to give the academic education required for the production of professional engineers. At present, the students are studying for the examinations of the United Kingdom engineering institutions, but the College is about to become a university college in special relationship with the University of London. There is, at present, only a very small handful of indigenous East African professional engineers, so that almost all these students, who reach graduate status and show reasonable ability, must rise quickly to senior positions in Kenya, Uganda, Tanganyika and Zanzibar, and have far greater influence than would normally be the case in more developed countries. The practical training of this very small number of students, as they become graduates, is a problem which must be solved now or the opportunity will be lost.

It is possible for many under-developed territories to give part of the graduate training quite adequately. Accepting that training facilities in the United Kingdom are limited, is it better to give two graduates one year's training each in the United Kingdom, with the second year in their own country, or to give only one graduate the full two years' training in the United Kingdom and leave the second graduate to get what he can in his own country or to go elsewhere? This is not a theoretical question but is a real problem on which many British engineers oversea would be glad to have advice.

Mr. L. S. Crutch: We have had a gloomy picture of the conditions which the F.B.I. scholars meet in this country. I cannot speak for any branch of engineering except light current, but we have had graduates from West Africa and other places with quite satisfactory results. The paper deals largely with manual work. We have not emphasized manual work, but have had satisfactory results in the laboratory or on testing. We always try to put them with a small team, and thus they get the information which they require. The contact may not be with professional engineers, but it is with men of experience who can explain the work to them.

Reference has been made to varying requirements for practical training in the conditions of membership of engineering institutions in different countries. It seems desirable that some degree of uniformity in this respect should exist. There are many engineering activities in which first-hand practical experience is almost essential to supervisory and management control. Is it not to be hoped that an increasing amount of affiliation between engineering institutions in different countries may take place in future, and that, in this way, uniformity of requirements for corporate membership will be achieved?

Mr. R. L. Lickley: It is important for the oversea graduate to have contact with other professional engineers, and with other people of his own age doing similar work. The British systems of graduate training are in many cases far too inflexible for this purpose.

The author has considered some of the important companies which give good training, and we have had from a representative of one of these companies a justification of their training. The following comment was received from one of the major electrical companies on a first-class South American graduate: 'An intelligent and useful apprentice. However, he could do with a little more practical experience with hand tools!' We have many graduates in my own company and probably have to make use of them earlier than we otherwise would, because they are the only people who understand the advanced mathematics which we now have to use. I asked a selection of them why they wanted graduate training, and without any exception their answer was 'The Institutions require it'. That seems to me completely wrong. If that is the only reason for their taking training in the works, the quicker we, as engineers, stop it, the better, or we shall get, as Mr. Bevan mentioned, disgruntled, dissatisfied and troubled people.

This applies to the oversea graduate, who sees only a short time in front of him in which to get information, but it applies equally to our own graduates, who see a very short time in which they can afford not to start earning substantial money and getting on with their proper training for doing their job. Somehow or other we must devise a system which will make more use of these young men. It was suggested earlier that companies should not be interested in graduates but in profits, but the future profits of any company which is involved in advanced technology are so closely linked with the graduates that, from the point of view of self-interest alone, we must look after them.

The enthusiasm which these oversea graduates have when they arrive is tremendous. They have come from all over the world, and very often they have great difficulty in speaking our language, but they master it, which is more than many of us do with the simplest of foreign languages. If British industry cannot ease its requirements or its training programmes to fit the oversea graduate better into the picture, these graduates will go to Germany, to France (which is now starting some very large schemes), to Russia and to the United States. That can only have an adverse effect on our position as a trading nation.

In other parts of the world graduates are not interested in workshop training. A graduate from an American university can get a job as a foreman on the shop floor without having been there before, and I have not noticed that American production suffers. The whole effect of our approach to graduate training at the present time suggests that our heels are too deeply in the mud of the past.

Mr. S. C. Chu: As an F.B.I. apprentice prior to the last war, I am glad to know that the scheme has, since my time, been developed over such a wide field and to cover so many countries. I was much benefited by the scheme and am still indebted to the many firms which gave me my practical training. I should have thought that conditions after the war would be better and that the present oversea apprentices would be much better off than I was, and I was surprised to learn many of the facts.

With regard to the training of mature and experienced engineers, it would be mistaken to treat these men as trainees. So far as I know these engineers are all well experienced and they come to this country to refresh their knowledge and perhaps to find new equipment. They are therefore not interested in doing any particular job for a long time.

On the participation in social activities by apprentices, I agree with one speaker who said that the trainee should stay with one firm for at least a year. In my time we never had a three-monthly change of firm, and this gave the apprentice more opportunity to meet the professional engineers in the firm. In general I think the F.B.I. and the firms involved should encourage oversea apprentices to get in touch with the professional engineers both inside and outside the firm.

Mr. G. S. C. Lucas: Is the author wise in collecting information from graduates at present in training in this country? Is this not like asking the patient what kind of treatment he would like? I ask this question because some years ago I was closely in touch with oversea graduates as chairman of an oversea association. A deputation of graduates came to me with a number of suggestions about the ways in which their training could be improved. In fact, the number of suggestions was equal to the number in the deputation. They suggested sending a questionary to all graduates in training. I suggested it might be better if they sent their questionary to engineers who had passed through the training and had had the benefit of several years' experience and who could say whether their training was of value to them or not. They did this and I have a copy of the report which they prepared from the results. It was encouraging to the graduates and gratifying to those who had been responsible for the training scheme. We need to collect information on training, but I believe we should seek it from those who have had the training and have had experience in using it.

The author states that very often oversea graduates want training different from that given to the home graduate. My experience is that they need a different training from that given to the home graduate but they usually want exactly the same training that the home graduate is given.

Mr. J. A. Kline (*Australia*): The Australian Post Office is particularly interested in sending graduates to England for training and experience, but of the various schemes under which this can be done, the F.B.I. scheme is the least attractive. We are disappointed that the training has come to be regarded as a second-best when it is based on such a fine idea for propagating in oversea countries the highly rated British engineering principles and practices. We have had a number of marked successes, but we have also had cases which have been unsatisfactory because of poor selection, unsuitable training or economic difficulties.

When a selection is made by the local committe, the Department is advised regarding the person selected and the subjects it has been agreed that he should cover. The selection has sometimes been quite surprising, and difficulties are immediately foreseen when taking into account the records and information available to the Department. It has been clear in a number of cases that more suitable men could have been chosen and more appropriate studies arranged. The Department is faced, however, merely with a decision whether or not to grant two years' leave of absence to the scholar.

I suggest that two scholarships should be made available to the Postmaster General's Department under an arrangement by which it can select the men considered most suitable and to plan the type of training which it is best for the student to take, bearing in mind his career in the Post Office. Similar allocations might be made to other organizations which have provided a regular number of students under the scheme. If this were done

I think that the type of person chosen could be improved and the risk of failure diminished.

It has already been stated that the type of training should be arranged specially for each individual, and I heartily endorse this plan. In England you have a 3-year course for university engineering graduation, followed by two years' graduate apprenticeship. The tendency is to put graduates from Australia into that 2-year graduate apprenticeship. Australian universities provide a 4-year course in engineering, and during that time the student does a good deal of practical work. He must undertake approved work as training during the vacations, and this is organized by the universities. When he completes his university course he has had, in general, a greater degree of practical training than is normally available to or is taken by the graduate in this country, and he therefore presents a totally different proposition for post-graduate works training; yet he is frequently put into the same course as a British graduate, and this does not work very well.

I suggest that every trainee from Australia should be given at least one major engineering project involving a wide scope of activity which should not be just practical work such as drilling holes or repetitive manual work. If the project involves bench work then let him do it, but whatever is included should be viewed as an engineering requirement. Reports should be made at regular intervals, and these should show that the student understands the engineering aspect of the jobs done and the engineering reason for each operation.

On the economic side I feel that there must be improvements. An engineering graduate in Australia at the end of his 4-year course is considered to be a fully trained man, and he commands a salary of about £1 000 per year. It is a general requirement that those chosen for the F.B.I. Scholarship shall have had a year in industry before being selected, so that they will understand the requirements of Australian industry before they come to Britain, and such a man will be getting a salary of something like £1 100 per year. It is a big reduction when he gets £450–£500 a year over here. We have had trainees who have not been able to make the grade financially and they have appealed to the Department to help them out of their difficulties. In fact, it is the present practice to ask each trainee who is selected whether he is sure that he can exist in England on the amount of the grant, and if he has any private means to cover the position should the expected difficulties arise. That is surely not good enough. Other speakers have referred to these difficulties, and it appears that some organizations are supplementing the amount given by the F.B.I. I suggest, however, that the F.B.I. itself should take the responsibility and increase the amount given to a student—perhaps by adding an oversea allowance to the graduate apprenticeship rate. If this were done the Scholarship would become attractive to a substantially wider field of graduates.

Mr. D. B. Welbourn (*communicated*): The paper uses the well-documented cases of F.B.I. and similar scholars to draw attention to the shortcomings of graduate training in British industry. Every week former pupils, now in every branch of the engineering industry, come to discuss with me their problems in industry, and each year a new batch of freshmen come into residence in my college who have just spent a year in industry before coming up. The picture which talking to these men builds up is depressing. The abler a man is, the more likely he is to be bored with the training he is given; and the larger the firm to which he goes, the more likely he is to be treated as though he were in a sausage machine. Those men who are given responsibility during their training, and a real job to do, are enthusiastic about it—unless, of course, they have got put on to work which they realize could be better done on a computer. Much play

is needed with the necessity for a trainee to be on the shop floor long enough to get to know the men; of course, it is valuable for a man to spend long enough on one typical machine tool to be able to earn a bonus on the current piece-work rates, to learn to argue with the rate-fixer and the inspectors, and where to place his bets. Most of his time will be wasted, however, unless he is also instructed as to what he is trying to learn, and introduced to the analytical approach to his situation such as can be found in books like 'Personality and Group Relations in Industry' by Fogarty or 'The Social Psychology of Industry' by J. A. C. Brown. The gap between theoretical engineering and what occurs on the shop floor is too large for most men to be able to bridge unaided. Once a man has mastered one tool, though, his time is merely being wasted in moving him on to a number of others; how many machine-shop foremen can use every tool in a modern machine shop? Must a professional engineer have tried his hand at every process that he might meet?

Unless more firms can be persuaded to take graduates, and men wishing to do sandwich courses, the present educational system for engineers in this country will soon break down. It will also break down unless firms give a better general standard of training than they are doing at present.

Comdr. K. W. Willans (*communicated*): I should like to comment on the paper as a mechanical engineer. The author poses the question 'Are we, in fact, making a colossal mistake?' I suggest that the answer is definitely 'No' as regards the scheme as a whole but 'Yes' as regards workshop training.

Manual training should be carried out in the graduate's own country prior to going to the university. Post-graduate work shop experience should be definitely 'in charge'.

The late Sir Claude Gibb, in his admirable letter, brings ou the importance of giving early responsibility to young men Most of us clamoured for it in our youth, and having asked fo it and got it, we had to 'make a go of it' with an audience waiting to see us fail. Having got through we had learned to stand on our own feet.

How now can minor positions of responsibility best be found' I suggest that the answer lies in the 41 500 small engineering works employing from 11 to 99 men. These works are run by highly skilled practical engineers, and it is safe to say that fa more than 2 000 of them would be glad to take an F.B.I. Scholar ship graduate in a position of minor responsibility. In such works, design, manufacture, sales, and in many cases the operation of the firm's products are carried out under the ey of the boss who would be only too glad to delegate work. A great failing of universities is found in failure to appreciate tha control of labour can only be learned on the shop floor, and ideally in small works.

To find a link between the F.B.I. and such works I should were I concerned with the F.B.I. scheme, make contact with the Institution of Agricultural Engineers. This active Institution uses a similar approach for its own graduates, and I feel sure would co-operate.

Looking back upon over 50 years in charge my lasting regre remains that after leaving school I did not go straight into a works and thence to the university, knowing, by then, what I wanted to learn there.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Dr. W. Abbott (*in reply*): The comments of Messrs. Goodall, Marshall and Lucas can be taken to represent the views of an organization which has done pioneer work in the field of graduate training. By experiment and development it has established a pattern of practical education which has won the respect and admiration of other firms and other countries. It is willing to take each case on its merits and provide the most appropriate training. With regard to Mr. Marshall's point about undue change, the F.B.I. type C scholars are mature engineers who want experience rather than training, and movement among a number of firms can be well justified. The movement of the younger men should, of course, relate to the conditions oversea, and the usual mixture is half manufacturing and half operational experience; this is not unreasonable, since the man from a developing country is less interested in manufacture than in erection, test and maintenance.

Mr. Waldram's reactions explain why some trainees show impatience. A young man from, say, Australia can get routine experience at home, and he comes here to learn something of the latest methods which are not readily available in his own country. He is avid for information, does not want to waste time and will not readily undertake repetitive work. He wants variety and in due course some responsibility, and many civil engineering firms recognize the reasonableness of his aims and go far to meet them. As Mr. Bellamy says, these young men have an inexhaustible energy to probe, examine and analyse.

Mr. Stock's remarks concerning Uganda are important and will be closely considered by the F.B.I.

The comments of Mr. Crutch on the light-current electrica industry are of considerable interest; it is clear that, by using graduates in teams on laboratory and test work, and by not stressing manual dexterity, he has achieved satisfying results.

Mr. Lickley's wise comments could not, in my view, b emphasized too much. We have to re-think the aims and object of graduate training, not only for the men from oversea but fo the home graduate too.

Mr. Kline's recommendations on selection will be given th most careful consideration by the F.B.I. Scholarships Committe in co-operation with the Australian Selection Committee. I full agree with his comments on the kind of training which Australia graduates should have, and our object now is to bring thi about.

The allowances for F.B.I. scholars are under continuous review and increases are about to be made, but not with the aim of having special rates for scholars from certain countries.

I regret that Mr. Welbourn's valuable and provocativ contribution was not made verbally and discussed. His fin; sentence is worth repeating: 'The present educational syster will break down unless firms give a better general standard of training than they are doing at present.' This is the theme of the paper.

NORTH LANCASHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By C. C. BACON, Member.

'EARLY PROBLEMS AND PRACTICES IN THE ELECTRICITY SUPPLY INDUSTRY ABOUT THE TURN OF THE CENTURY'

(ABSTRACT *of Address delivered at* PRESTON *12th October*, 1960.)

In 1819 The Institution of Civil Engineers was founded—'civil' as opposed to 'military'. Fifty-two years later our own Institution was founded as The Society of Telegraph Engineers, and in 1888 it became The Institution of Electrical Engineers.

In 1813 Michael Faraday entered the Royal Institution, his early work being connected with chemical investigation. In 1831 he discovered magneto-electric currents, or the principle of electromagnetic induction. Several working exhibits of Faraday's apparatus are in the Science Museum, London.

Following this period, there was no rapid progress, largely because no system of measurement in electrical units had, as yet, been devised. The British Association in 1861 appointed a committee to determine what form these measurements should take, and it was this that did more than anything else towards the advancement of the electrical industry at that time.

At first, currents were measured by their chemical effects and deflection galvanometers were used, graduated in degrees, and telephone linesmen added a scale to their instruments which they used when investigating line faults. This read: 'Very good', 'Good', 'Fair', 'Requires attention' and 'Bad'.

The Paris Exhibition of 1881 gave a great impetus to electrical matters generally.

Generators and Switchgear

The early generators following Faraday's discovery gave alternating current, but as soon as the commutator was introduced, d.c. generators were developed and the a.c. generator was, for the time being, relegated to the background.

The first d.c. generators gave a pulsating current; a steady voltage was obtained with improvements in armature construction, but it was not until Hopkinson and Kapp developed dynamo design that the machines became anything like efficient and the mystery of the magnetic field was explained.

Low-speed revolving-field salient-pole alternators were developed about 1885, followed by Parsons's turbo-alternator. The first turbo-alternators went into commission in 1889 and had a capacity of 75 kW at 1 000 V. They were single phase and ran at 4 800 r.p.m., giving a frequency of 80 c/s.

A fundamental advance was effected by Brown in 1901 when he introduced a cylindrical rotor; this was followed in 1911 by a single-piece solid forging.

The first turbo-alternator was provided with a form of automatic voltage regulator. A fan was mounted on the turbine spindle which exhausted air from a leather bellows, the latter being attached to the main steam valve. Air leakage from the bellows was controlled by an iron armature mounted on top of the generator field magnets, and thus the amount of steam admitted to the turbine depended upon the flux in the field magnets.

The switchboard, in the strictest sense of the word, is not an indispensable adjunct to an electrical installation, and in fact was unknown for several years after the introduction of electric lighting. It first came into use, in a very crude form, as a matter of convenience; it was gradually elaborated, and at the present time is regarded as a part of the system only second in importance to the generator.

A large double-decked switchboard built about 1894 was used for the control of a.c. and d.c. generators and feeders. Five panels on the lower floor were used for control of five 1 000 kVA 3-phase alternators. Each panel had a pilot lamp, two ammeters, two voltmeters, 2-pole double-throw switches, two sets of field plugs and two rheostat face-plates. The next two panels with a bell and clock were station panels, the next four exciter panels and the last two d.c. feeder panels. The balcony was devoted to a.c. feeder panels; the single-phase circuits connected to these could be interchanged by means of plugs and sockets.

A second switchboard handled the high-voltage transmission currents that came from the power station. It consisted of three panels, each made of two marble slabs placed one behind the other. Switching was accomplished by means of plugs and sockets. The terminals connected by the plugs were mounted on the marble slabs, the latter being separated by a space of 2 ft. There were two incoming 3-phase lines and three groups of 3-phase transformers, and the arrangement of the sockets on the switchboard panels was such that either one of the incoming lines could be connected with any one of the groups of transformers.

The first 10 kV switches in use at Deptford were designed by Mr. Ferranti, and when initially installed there was trouble when a switch was opened. The engineer used what he called an 'oar', which he waved about to cause a draught, thus blowing out the arc.

Power Stations

Here are a few details of the supply to the Paddington district in 1887. The supply was alternating current and was fed to a large switchboard for distribution via five substations; from this board there branched a double system of mains which ran everywhere side by side. One-half of the mains was connected to the first machine and one-half to the second, so forming an excellent arrangement for the prevention of total extinction of the light.

Willans engines were referred to quite frequently in the early days, and here is an interesting comment about them. At an Institution meeting in 1895 a member who had a great many of these engines under his care said, 'I do not really know what there is inside a Willans engine, but I do know there are three holes in it—one hole where the steam goes in, another where the steam comes out and another where you put oil in, and if I only pay proper attention to these holes everything will go right'.

Details of the Blackpool electricity works are as follows: one 100 kW alternator, two 50 kW alternators and three arc dynamos. The station could supply 12 500 8 c.p. filament lamps and 165 2 000 c.p. arc lamps.

Uniform with all the rest of the work and in order to provide for the perfectly safe working of the plant at every point, the terminals to which the 2 000 V h.v. mains were connected were securely boxed in by polished-wood lagging, so that they could not be touched except by the proper officials.

In the engine room there was a magnificent switchboard of enamelled slate on which were arranged appliances for controlling the circuits and maintaining a constant voltage. It also included synchronizing equipment which was arranged to slide along a guide rail and to be automatically connected to the adjacent circuit.

Mr. Bacon is with the North Western Electricity Board.

Cables and Protection

In the 1880s distribution cables consisted of bare conductors installed underground in culverts. Following 1890 high-voltage single-phase cables were being made as the result of the pioneering work of Ferranti for his 10 kV scheme. In 1901 the first 3-phase cables were used, but the Government limited the voltage to 5 kV and the capacity to 100 kW. It was during the First World War that 33 kV cables were first manufactured. and it was many years before they operated satisfactorily following the introduction of the H-type cable with a screen round each conductor.

Air-break switchgear was used extensively, but shortly before 1900 oil-break and water-break switchgear was tried, the main object being to quench the arc in as small a compass as possible.

The water-break switches were mounted horizontally on the top of the switchboard and operated by levers immediately below. In passing through the switch the main current was carried by heavy laminated contacts and a substantial bridge-piece fixed on insulation to a carriage pivoted in a bearing passing to the base. In parallel with these contacts were two blades which dipped into oil or water pots directly in front of the main contacts. In opening the switch these latter passed clear of the laminated brushes before the auxiliary contacts had left the liquid, so that any arc which was likely to form was quenched within the pots.

It was soon after 1900 when the first completely metalclad switchgear was introduced. The first unit made by a well-known firm is in the Science Museum, and it is remarkable how similar it is to that manufactured today by the same firm. This does not indicate that no progress has been made with development, but rather illustrates the sound basis upon which the early gear was designed.

At this period, when voltages up to 40 kV were being used, the switchgear would not stand up to fault power available and it was found necessary to install two breakers in series. The switch opening first inserted resistance to reduce the duty on the second breaker.

Mr. Ferranti devised a very ingenious method for protecting transformer circuits from the risk of partial earth. This method required the mid-point of the secondary circuit to be permanently earthed. It was perhaps more useful as a testing device for partial grounds, as the fire offices' regulations did not generally allow any part of the consumer's circuit to be earthed. But for power plants, where these restrictions did not obtain, the device was most useful.

There were two small transformers across the secondary mains, with an earth wire from their point of junction. Their primaries were arranged in opposition and normally no current flowed through them. If, however, another earth, full or partial, was made in one of the secondary mains, the corresponding transformer ceased to deliver current, and the balance of voltage being upset, a current flowed in the secondary circuit and melted the fuse, thereby allowing a conical plug to drop into a split cup. This short-circuited the secondary circuit and blew the primary fuse.

Load Curves and Fault Location

One of the earliest references to a load curve was made in 1888. It concerns a residential district in London which was wired for 10 000 lamps, and the plant was equal to the demand of 600 kW. It reads as follows:

> The number of lamps is small until about 3 p.m. .... on a winter afternoon; it then increases steadily until about 6.30 p.m., when the curve goes up with a rush. About this time a great number of people are preparing for dinner and probably the lights are on both in the dining room and bedrooms. The curve falls, and at about 8 p.m. it sinks gradually until 10 p.m. A great many people appear to go to

bed about this time, but a few sit up until 1 a.m.: until 6 a.m. th next morning hardly any supply is taken. . . . The important fac has been obtained that the average daily output of a station through out the year is less than one-third of the total capacity of th generating plant.

It is evident that in so extensive a system of lighting a short circuit now and then between the lamp wires and earth canno altogether be avoided. Many of the lamps have been fitted t existing gas fittings and are beyond the daily supervision of th company's officers; the faulty place is often not easily accessible s that the first step taken is to discover on which of the two circuit the trouble has occurred. Two lamps are connected in series an the centre point earthed. This indicates which wire is faulty. series of fusible plugs are connected between the sound circuit an earth and the one that does not blow indicates how many lamp away is the point of the fault; the position of the fault is thu localized and the company proceed to remedy the defect withou interfering in the slightest degree with the rest of their system.

Consumers' Meters

In 1887 Edison electrolytic meters were used:

> The quantity of electricity passed through the cell is calculate by the loss of weight of the plate. An employee of the society visit every meter monthly, taking away the old cells and substituting ne ones. A book is kept to record the weights of the plates. The weak point of the system is the removal of the cells which leaves th adjustment of the account to be paid entirely in the hands of th Electric Light Company; in spite of this drawback it is stated tha there has not been a single complaint from consumers during th four years in which the meter system has been in use.

System Earthing

During the first decade of the 20th century there were wide differences of opinion as to whether an a.c. system should have a earthed or unearthed neutral. A report given to The Institutio stated that the two advantages of an earthed system were th limiting of the voltage between live wires and earth, and th possibility of cutting off any wire or feeder in the event of a earth on it. 'The chief objection to earthing is that the system cannot be operated with an earth on any live wire.'

Arguments were put forward as we know them today, and the return flow of capacitance currents when one live conducto was earthed was understood. Balanced protection was designe to detect the flow of earth currents; the term 'zero sequence current' had not appeared.

Where generators supplied a cable system it was satisfactory t take all neutrals to one busbar and then connect this to earth If the generators were not similar, circulating current might flow but unless this was considerable it was ignored. If it was con siderable only one machine at a time was earthed. This lef the earthing to the memory of the attendant; if he forgot t earth the system this was not very important as trouble occurre only in the case of a cable fault.

The value of resistance used on the h.v. system was determine so as to give the minimum current necessary to cause automati disconnection of the circuit. Cast-iron grid resistors were used and it was soon found that the positive temperature coefficien of the grids was a disadvantage, since, if a circuit did not tri in the first second or two, the current fell and the fault persisted It is interesting to note that the London Electric Power Co devised a carbon resistor with a negative temperature coeffi cient. This consisted of 72 fire-clay troughs 22 in long and 8 i wide, filled with a special carbon powder. It was used on a 11 kV system and passed 200 A at the moment the fault occurred

About this time thought was being given to injecting curren at a frequency of 200 c/s into the system so as to select a differen meter during peak periods and thus encourage off-peak loading

In concluding the review of early problems and practices, few extracts from the first edition of the Wiring Rules publishe by The Society of Telegraph Engineers and Electricians wer discussed.

THE LOGMOTOR—A CYLINDRICAL BRUSHLESS VARIABLE-SPEED INDUCTION MOTOR

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SUMMARY

In a conventional induction motor the synchronous speed at the rotor surface is set by the phase difference between currents in adjacent slots and the spacing of the slots. The synchronous speed may be increased by changing the phase of the current in each slot progressively so as effectively to stretch the poles. The paper describes a transformer arrangement giving a multi-phase output, which can provide such a 'phase-stretching' system to be used to supply the stator of a squirrel-cage induction motor. The transformer is similar to a conventional phase-shifting transformer, except that the pitch of each coil of the primary is proportional to the log of its distance from a fixed point in the system. The primary and secondary of the transformer are analogous to the C and D scales of a slide-rule, and movement of the primary relative to the secondary results in a variation of the phase increment between adjacent secondary coils. The secondary is connected to the stator winding of the motor in such a way as to provide a uniform-velocity field in the latter, the velocity being varied by adjusting the position of the primary of the transformer. The method of construction of an experimental machine is described and test results over a speed range of 4 : 1 are included.

(1) INTRODUCTION

In an earlier paper,[1] the concept of the linear induction motor was described by supposing that a conventional cylindrical stator could be cut open and rolled out flat. The synchronous rotational angular velocity $2f/n$, where n is the number of poles around the periphery and f is the supply frequency, is then replaced by a synchronous linear velocity $u_s = 2pf$, where p is the pole pitch. The operation was demonstrated by using a model of a stator made of rubber. The model was split axially and held together by a zip-fastener. When the latter was opened, the stator could be rolled out flat. In this condition the model was also capable of being stretched. If the model were stretched in the direction of the rotor velocity u_r so that the length of the model was increased to k times the initial length, the new pole pitch would be kp and yield a new synchronous velocity $u_s = 2kpf$. Thus, variations in k would produce variable speed.

Various attempts[2,3] have been made to obtain variable speed by using this 'pole-stretching' technique. Usually the windings of the various poles have been mounted on separate iron structures movable relative to one another. This difficulty was avoided in the authors' variable-speed motors[4,5,6] by adjusting the angle between the direction of motion of the field and the direction of motion of the rotor, so as to give the effect of variable pole pitch as seen from a point on the rotor during rotation. All of these methods depend on changing the actual or apparent spacing of conductors carrying currents of fixed relative phase.

Alternatively, if a fixed structure is used, with conductors in fixed positions relative to one another, 'pole stretching' can be

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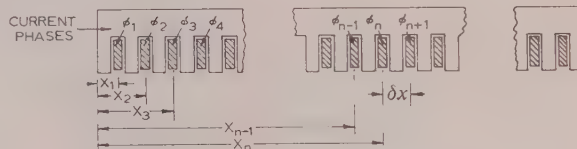
Fig. 1.—The problem of 'phase stretching'.

achieved by varying the phase displacement between the currents in adjacent conductors. Thus, referring to Fig. 1, if ϕ_n is the phase of the current in slot n, $x_n - x_{n-1} = \delta x$ is the slot pitch, and $\phi_n - \phi_{n-1} = \delta\phi$, the synchronous velocity is

$$u_s = 2\pi f \frac{\delta x}{\delta\phi}$$

If u_s is to be constant along the length of the block, $\delta\phi$ must be everywhere the same; but if $\delta\phi$ can be varied simultaneously along the whole length of the block, then u_s can be varied. The pole pitch of the winding is $\pi\delta x/\delta\phi$, and is 'stretched' by changing $\delta\phi$. This method might be called 'phase stretching' to distinguish it from 'pole stretching'. The paper is concerned with the development of a 'phase-stretching transformer' designed to supply currents of appropriate phase to a stator block with the object of providing a velocity variation over a wide range.

(2) A PHASE-STRETCHING TRANSFORMER

A conventional wound-rotor induction motor in which the rotor is held at standstill constitutes a conventional rotary phase-shifting transformer, provided that the angular position of the rotor can be adjusted. Such machines usually carry a 3-phase wound rotor. If a squirrel-cage machine were to have one end-ring removed, the free ends of the m rotor bars would provide an m-phase system of a.c. supply when the stator was energized to produce a rotating magnetic field in the air-gap. With the rotor fixed in position the phase of the induced e.m.f. in one rotor bar would be fixed in relation to the phase of the stator supply. A change in the angular position of the rotor would change the phase of the induced e.m.f. in each rotor bar by the same amount, the phase difference between the e.m.f.'s in adjacent bars remaining the same.

The structure just described is characterized by having uniform slotting of both rotor and stator and by having a stator winding of constant pole pitch. An alternative arrangement is shown in the developed diagram of Fig. 2(a) and (b). Here, both rotor and stator blocks have 80 slots, numbered 10–89 for convenience, but the slots, unlike those of the conventional phase-shifter, are arranged in a non-uniform manner such that the displacement of a slot from the left-hand edge is proportional to log $(x/10)$, where x is the slot number. For the sake of clarity, not all the slots are drawn in this Figure; the first 20 are shown
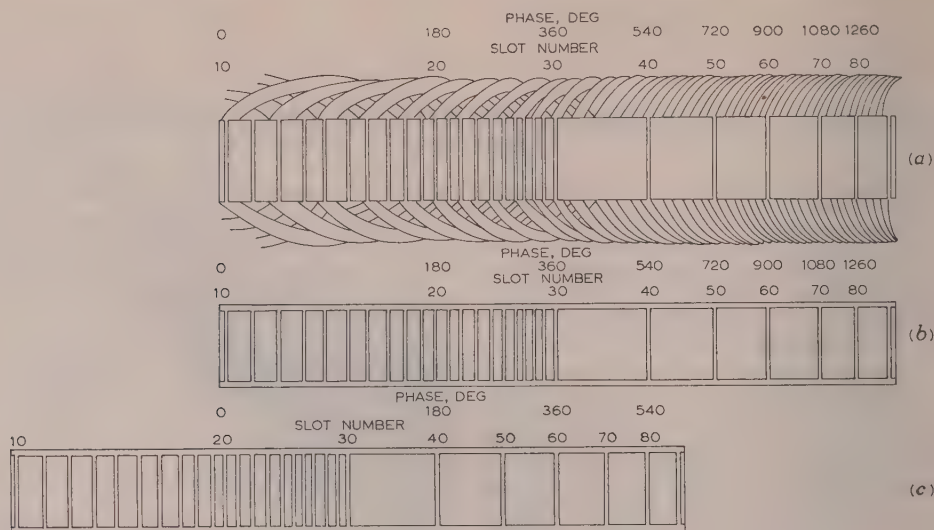
Fig. 2.—The principle of 'phase stretching'.

(a) Primary.   (b) Secondary.   (c) Secondary after displacement.

in full, thereafter every tenth slot is shown. The stator or primary winding is an exact copy of a conventional stator winding with 80 slots, like-numbered slots carrying corresponding coil sides. The only difference lies in the spacing of the slots. The stator shown in Fig. 2 carries 8 pole pitches, so that the phase increment per slot of the currents in the stator is constant at 18° along the block, but the pole pitch decreases from left to right. With good coupling the rotor or secondary bars will carry equal and opposite currents, and will therefore also exhibit a phase increment of 18° per bar. If one end-ring is removed, as before, secondary-bar e.m.f.'s will exhibit an 18° increment per bar.

Although Fig. 2 is introduced as a developed version of a cylindrical structure, it could equally well relate to a linear structure, and it is convenient to consider it as such for the moment. With this proviso, Fig. 2(c) shows the result of displacing the secondary relative to the primary, so that bar 20 of the rotor is now opposite slot 10 on the stator. Because of the logarithmic spacing of the slots, which corresponds to the relative spacings of the incremental tenths on a slide-rule, this displacement brings bar 40 on the secondary opposite slot 20 in the primary, bar 60 opposite slot 30, and so on. Thus, discounting overlap, any 20 bars on the secondary now span 10 slots on the primary, and the incremental phase change per bar on the secondary is therefore 9° instead of 18°. Similarly, if the rotor is displaced from the centre position through an equal distance in the opposite direction, the phase increment per bar on the secondary becomes 36°. Intermediate, or greater, displacements yield corresponding results, as may be checked by using the C and D scales of a slide-rule as a model, or by reference to the analysis of Section 12.1.

Thus, in principle, a winding designed to produce a travelling field with pole pitch decreasing according to a logarithmic scale, mated with a movable secondary block carrying conducting bars arranged on a similar logarithmic scale, provides a multi-phase output from those bars, and movement of the secondary relative to the primary yields continuous variation of the phase increment between adjacent output points. This process has been called 'phase stretching' for want of a better name. The multi-phase output is unusual in two respects. First, owing to 'variable overlap, the number of energized output points, or phases, is variable, and secondly, in proceeding from the first energized point progressively through the phases to the last, the total phase rotation in general will not be a multiple of 360°. These peculiarities may limit general application of the device but do not hinder its use in variable-speed motors.

(3) APPLICATION TO VARIABLE-SPEED MOTORS

Fig. 3 shows in developed form at (a) and (b) a phase-stretching transformer as described above, used to supply the stator (c) of an induction motor with a squirrel-cage rotor (d). The output points of the transformer section are cross-connected to uniformly spaced bars in the motor stator slots. This stator therefore carries currents which show a uniform phase increment per slot. The transformer is capable of movement relative to the secondary and is shown in Fig. 3 in two positions, A and B. The stator is drawn only in part in position A for the sake of clarity. With the transformer primary in position A, the phase increment in the motor stator can be seen to be 18°. When the transformer primary is moved to the position B, the phase increment is seen to be 9°. Variation of phase increment produces a corresponding change in the synchronous speed of the stator field, and hence of rotor velocity. In the linear form 'overlap' will not cause any particular difficulty; it will merely result in part of the stator being un-energized and part of the primary unused.

The diagram can, however, equally be related to a cylindrical form by first folding the primary on to the secondary, face to face; similarly folding the motor rotor on to the motor stator, and then rolling both sections into cylinders, the transformer primary and motor rotor being inner members, and the transformer secondary and stator being outer members. The general form of the machine is shown in Fig. 4. In the cylindrical machine, overlap of primary and secondary can be harmful because the small-pole-pitch end of one will be mated with the large-pole-pitch end of the other. This difficulty can be overcome in a number of ways, for example, by omitting part of the primary winding so that the 'overlap' is always un-energized. Speed adjustment is obtained by rotating the inner member of the right-hand section, which is the wound primary of the phase-stretching transformer.
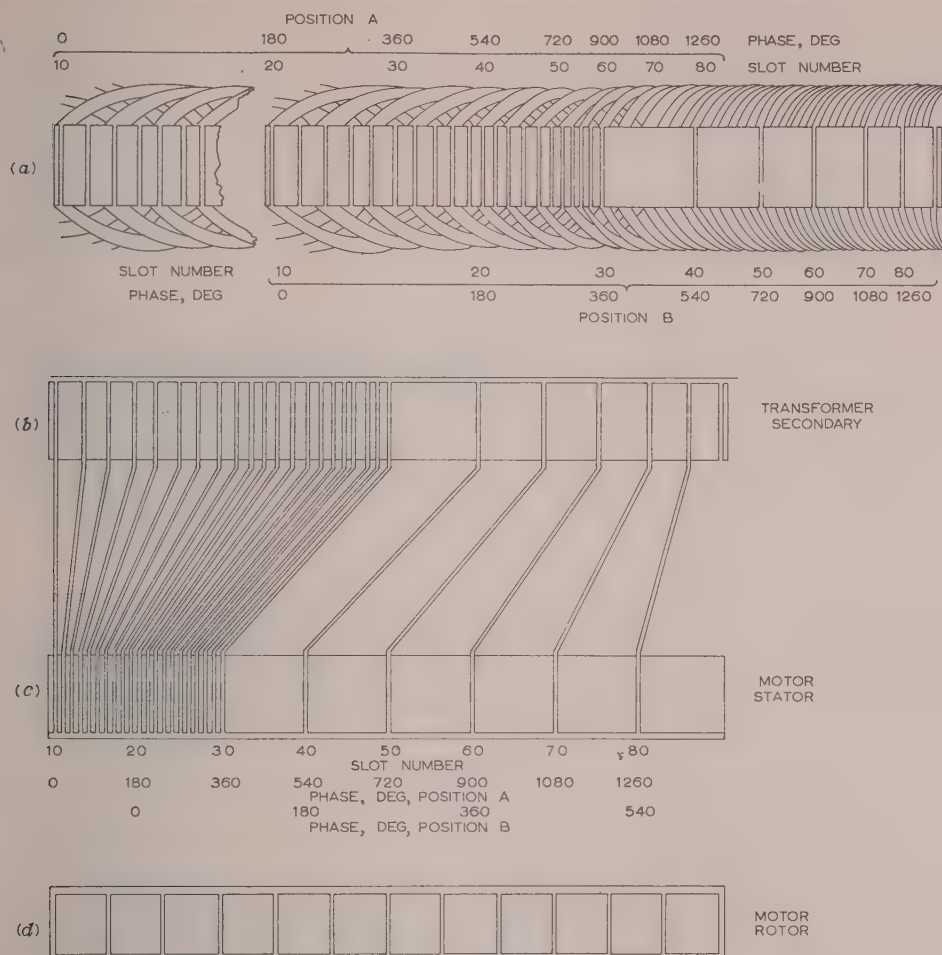
Fig. 3.—Principle of the log motor.

(a) Transformer primary in two positions.
(b) Transformer secondary.
(c) Motor stator.
(d) Squirrel-cage rotor.
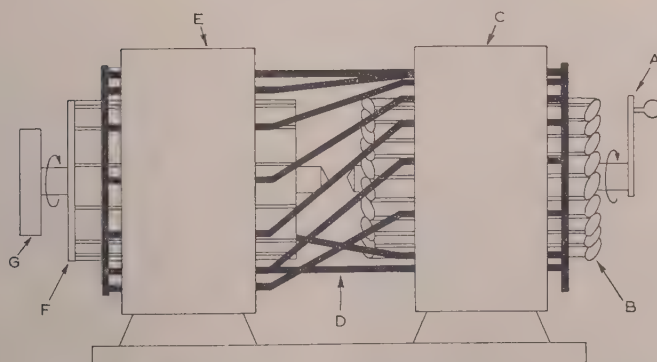
Fig. 4.—Form of construction of transformer and motor as a unit.

A Speed-adjusting handle.
B Transformer primary.
C Transformer secondary.
D Interconnectors.
E Motor stator.
F Squirrel-cage rotor.
G Output shaft.

(4) EXPERIMENTAL MACHINE

The winding plan of the first experimental machine is shown in developed form in Fig. 5. It will be seen that all the iron members are uniformly slotted but that the windings are distributed in the slots in a non-uniform manner.

(4.1) Primary Winding

The transformer primary is wound in 54 slots to provide 8 poles, so that the total phase change along it is 1 440°. The logarithmic distribution required is obtained by mixing con-

PHASE CHART

KEY TO PRIMARY DIAGRAM

(a)
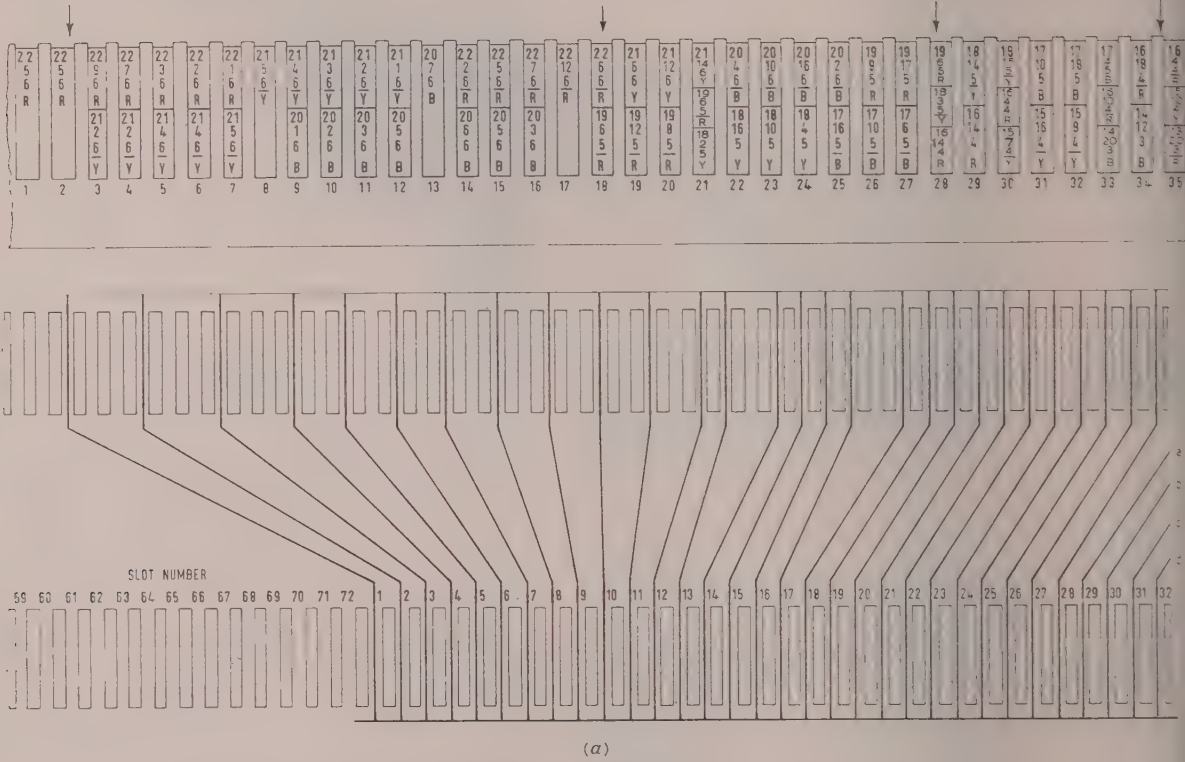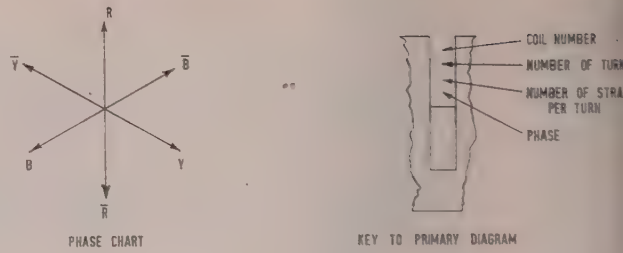
Fig. 5.—Winding plan of a logarithmic motor.

ductors of different phases in the various slots. If the net current in slot n is arranged to have phase

$$\phi_n = \frac{1\,600°}{10}\,\text{antilog}_{10}\frac{n}{54}$$

with n ranging from 0 to 54,* then ϕ_n ranges from 160 to 1 600, i.e. a range of 1 440° equal to 8 poles. The positions on the winding corresponding with pure 'red-phase' currents, either positive or negative, are shown on the diagram. At the right-hand end the winding is almost exactly a 'one slot per pole per phase' winding, but the degree of 'spread' increases greatly towards the left, until at the left-hand edge it is equivalent to 10 slots per pole per phase. The winding used is a double layer winding and each coil has the same number of turns. In order to make maximum use of the slot depth, the number of strands per conductor is increased from right to left. Because the 'spread' increases from right to left, the current per slot increases from left to right. Section 12.2 shows that the

* In a cylindrical machine with 54 slots, slot 0 and slot 54 are one and the same.
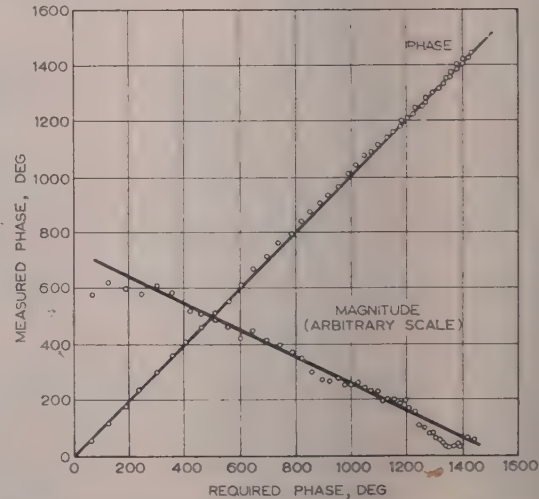
Fig. 6.—Test for current distribution in the primary winding.

appropriate formula for the current density, J_T, at position y from the start of the winding is $J_T = J_S \alpha \lambda \varepsilon^{-\lambda y}$.

Fig. 6 shows the measured phase and amplitude of the currents in the slots plotted against calculated values of ϕ_n. The phase error nowhere exceeds 30°. The amplitude shows the right kind of variation except for the beginning and end, where current amplitudes are low owing to the underlap and overlap of the two layers of the winding. Tapping points were provided in the vicinity of each of the 'red-phase' markers to enable less than poles to be energized if desired.

when this occurs the pairing process is best performed by taking successive values of s and finding the corresponding value of r. The resulting set of interconnections is shown in Fig. 5.

Each interconnecting bar was made up of 20 insulated conductors of 0·116 in diameter. They were arranged accurately in each slot in ten layers of two; each bar was partially transposed in passage from one block to the other, so that the conductors at the top of the slot in one block were at the bottom of the slot in the other. End-connections were made by soldering to stout copper rings.

(b)
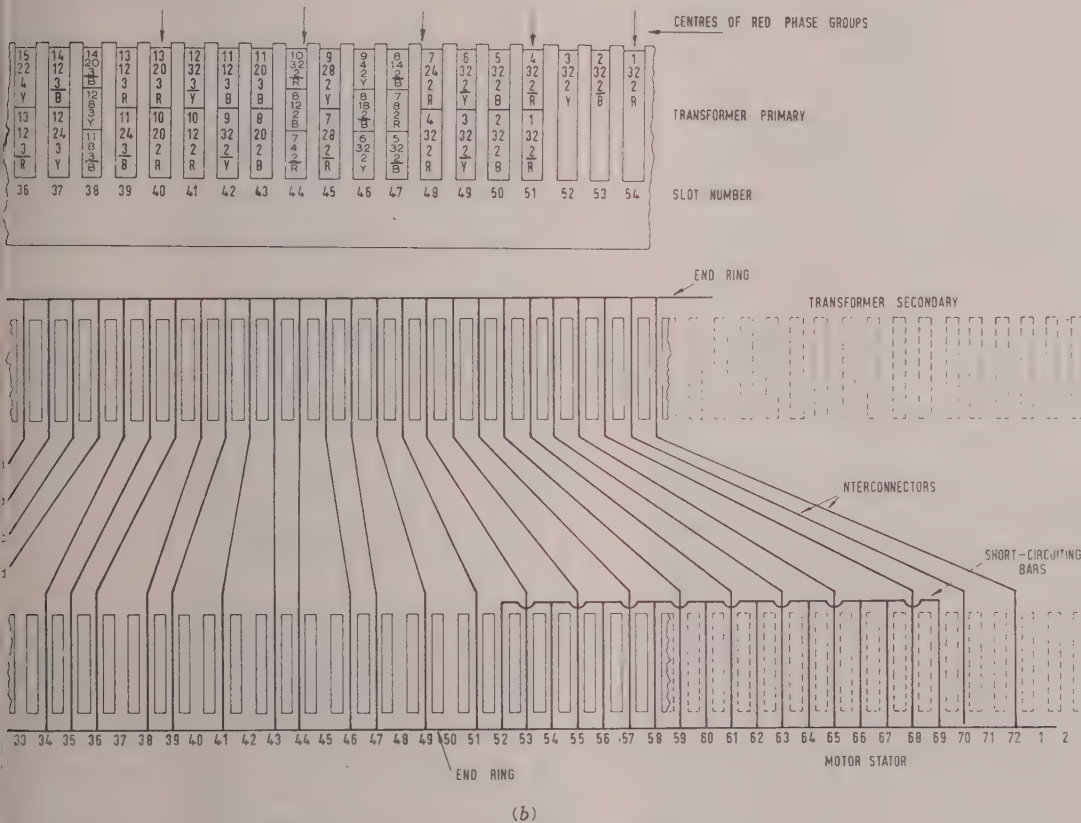
Fig. 5 (continued).

4.2) Transformer Secondary and Motor Stator Interconnections

The secondary and stator blocks each have 72 uniformly spaced slots, but the interconnections between them are required to transform a logarithmic distribution of phase into a linear one. Starting at the left hand of the motor stator, slot 1 can be assigned a phase of 160° to correspond to slot 1 of the transformer primary. The phase increment per slot along this block is everywhere 1 440°/72 = 20°, and hence the phase in slot m is $\phi_r = 20r + 160r$.

The phase ϕ_s in slot s of the transformer secondary is

$$\phi_s = 160° \text{ antilog}_{10} \frac{s}{72}$$

By listing ϕ_r and ϕ_s for slots 1 to 72 and starting at the left-hand end, it is easy to choose the value of s which corresponds most nearly in phase to each value of r. At first, each value of r will find an individual partner in s, with empty slots intervening between successive values of s, but, as the process proceeds, successive values of r will correspond with the same value of s;

Fig. 7 shows the result of a test of the transformer and motor stator, with the motor rotor removed. The amplitude and phase of the currents in the stator bars are shown as a function of the stator slot number. For this test the starting-points of the primary and secondary windings were aligned. The phase is seen to be a linear function of slot number apart from small errors not exceeding 25°. The amplitude is reasonably constant, except at the right-hand end, where it shows peaks at fairly regular intervals. These peaks are due to variation of slot alignment between the primary and secondary of the transformer. The ratio of slot numbers is 54 : 72, which results in slot alignment occurring every fourth stator slot. The effect is greatest at the right-hand end, because here the pole pitch is short and the slotting relatively coarse. The effect could have been reduced by skewing the primary slots, but a better solution, and one to be used in later models, is to use equal numbers of slots.

Fig. 8 shows curves similar to those obtained in Fig. 3 with the primary displaced to the left of the mid-point through an angle corresponding to log 2. It may be seen that there is a consider-

able range over which the phase is linear with slot number, and of about the expected slope, i.e. 40° per slot. At the right-hand end, however, the phase curve changes slope and falls to about 4° per slot. This is due to the left-hand end of the primary in Fig. 3 overlapping the right-hand end of the secondary. Reference to the amplitude curve, however, shows that the
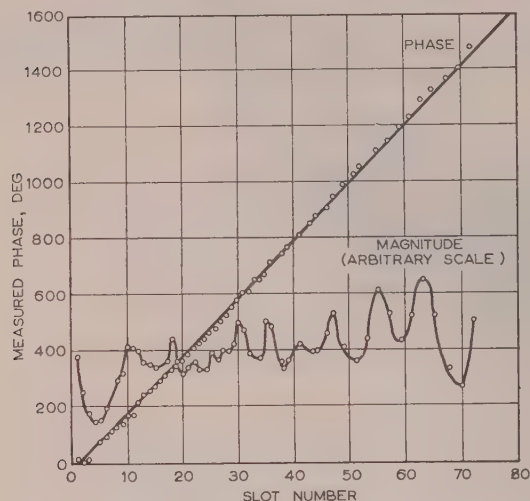
Fig. 7.—Test for current distribution in the motor stator.
Primary and secondary aligned.

current density is reduced by a factor of ten over this range; this part of the curve can therefore be ignored.

Fig. 9 shows the effect of displacement by the same amount in the opposite direction. Now there is a portion at the right-hand end which shows the expected phase slope, 10° per slot, but this is preceded by a portion showing 100° per slot, over which the current density is very high. Again this is due to overlapping, but this time the right-hand end of the primary, where current density is high, is overlapping the left-hand end of the secondary, where conductors are more widely spaced than on the motor stator. The high current density is therefore further increased. The early, incorrect part will therefore be dominant, and a low speed will result. If the high speed corresponding to the right-hand part of the curves is required, it will be necessary to disconnect that part of the transformer primary which overlaps the left-hand end of the secondary in Fig. 3.

These results show that the 'phase-stretching' transformer works as anticipated, and also that it can provide a configuration of current in a motor stator such as will produce an adjustable speed.

(5) MOTOR ROTOR

The rotor had 54 slots and each slot contained four insulated wires each 0·116 in diameter. Rotor resistance could be adjusted over a 4 : 1 range by connecting the appropriate number of rotor conductors to the end-rings.

(6) EXPERIMENTAL RESULTS

For the first test the transformer primary and secondary were aligned as in Fig. 3 (position A) to produce 8 poles on the motor stator. Torque/speed and other characteristics are shown in Fig. 10 with the intake current held constant. These curves show the characteristic shape associated with induction motors; maximum torque occurs at $7\frac{1}{2}\%$ slip, which indicates a rather
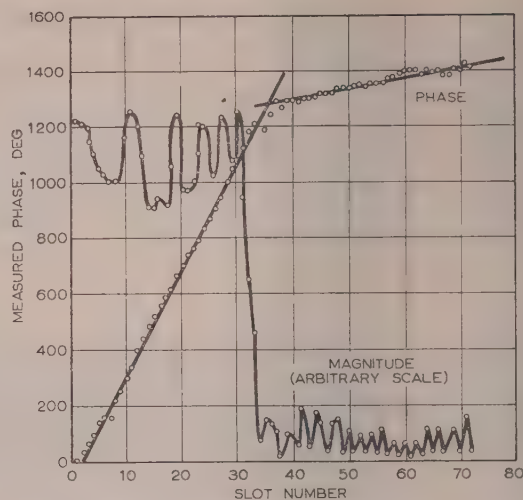
Fig. 8.—Test for current distribution in the motor stator.
Primary displaced to the left by an angle corresponding to log 2.
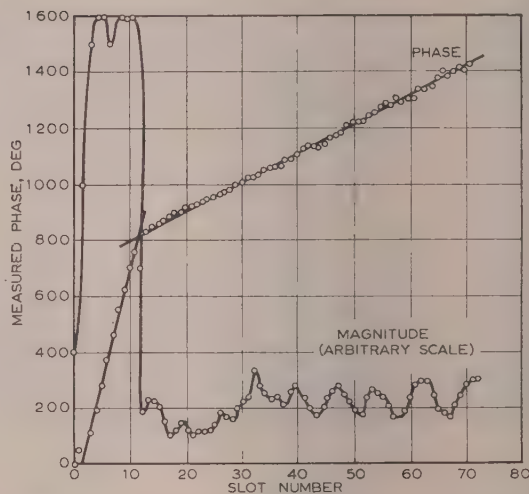
Fig. 9.—Test for current distribution in the motor stator.
Primary displaced to the right by an angle corresponding to log 2.

high rotor resistance. The peak efficiency is rather low, namely 63%. Curve (b) shows intake power, P_t, less 'synchronous power', $T\omega_s$, where T is the torque and ω_s the synchronous angular velocity. In a conventional machine this curve represents the sum of stator copper loss, iron loss and stray load loss. By measuring the intake power with the rotor removed from the motor stator, it is possible to obtain an estimate of copper loss per ampere squared; this corresponds to the short-circuit test on a transformer.

By measuring intake power with the rotor inserted, but with all rotor bars disconnected, it is possible to obtain an estimate of iron loss; this corresponds to the open-circuit test on a transformer. Both experiments have been done and used to estimate iron and copper losses in Fig. 10. These are shown at (d) and (c). Curve (f) is the sum of (c) and (d) and may be seen to approximate closely to (b). Thus the poor efficiency can largely be ascribed to conventional causes rather than to any unexplained property of the unconventional winding.
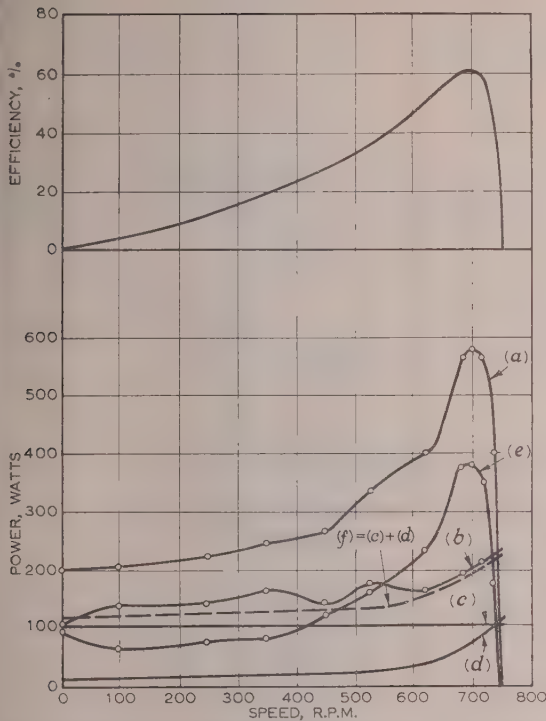
Fig. 10.—Brake test at constant current with primary and secondary aligned.

(a) Intake.
(b) Intake synchronous power.
(c) Estimated copper loss.
(d) Estimated iron loss.
(e) Synchronous power.

Fig. 11.—Speed variation with change in primary position.

(7) VARIABLE-SPEED WORKING

Fig. 11 shows the results of an attempt to obtain variable-speed working. For this test only the first four poles of the winding were connected, for the reason given in Section 3. As a result only part of the motor stator block was energized. The initial setting was for 750 r.p.m. as in the previous experiment. As the transformer primary was turned there was at first very little speed increase, but at about +30° the speed suddenly increased to near 1 000 r.p.m. Further turning gave relatively little speed increase. The primary was next turned back towards zero, and there was at first very little speed reduction, until, at about 25°, the speed returned abruptly to about 750 r.p.m., thus forming a 'speed/angle' hysteresis loop. As might be expected, the machine showed a marked preference for the speeds corresponding to even numbers of poles. This was because, as the rotor rotated, it carried flux round from the end of the energized part of the stator block back to the beginning of the block. The phase of this 'carried-over' flux, relative to the current at the entry edge of the energized part of the stator block, depends on speed, and either additional positive or negative torque may result.[6]

The effect of a carried-over flux can be eliminated by arranging to destroy the rotor flux between exit from the trailing edge and entry to the leading edge of the energized part of the stator block. For this purpose addition bars were introduced into the motor stator. These are shown in slots 52 to 69 in Fig. 5, and are connected to the end-ring at the top end only. If the free ends of these are short-circuited to each other, then, provided that they are of low resistance, flux cannot readily penetrate the stator block between the extremities of the short-circuited
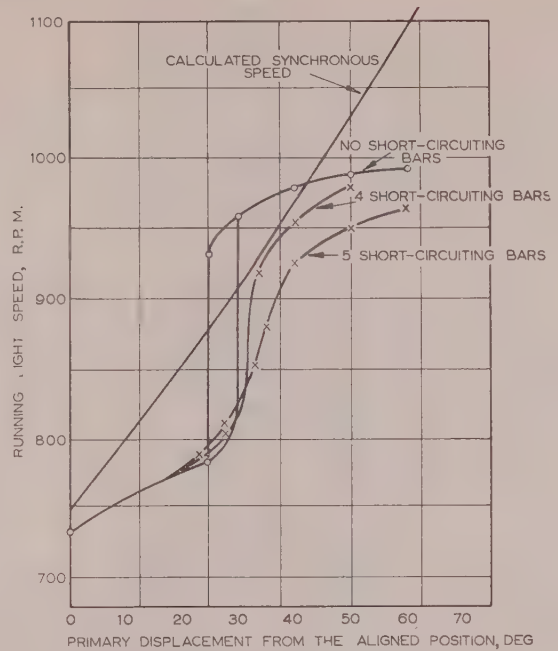
section. The flux in a rotor element passing under this short-circuiting grid is therefore severely attenuated, and sensibly 'dead' rotor is fed continuously to the leading edge of the energized part.

Fig. 11 shows the result of short-circuiting four of these bars. It may be seen that the hysteresis effect has disappeared, though there remains some obvious distortion of the speed/angle relationship. Short-circuiting a further bar reduces the distortion, but at the expense of additional losses, since rather heavy currents flow in the short-circuited bars.

With these five bars connected the next experiment was designed to explore the extent of variable-speed working available. For this purpose the first six poles of the winding were used. The test was made with a fixed load-torque of 3·3 lb-ft, and at each speed setting the voltage supplied was adjusted to yield the maximum efficiency.

The results are shown in Fig. 12. It may be seen that speed variation can be obtained over a range of 4 : 1. Curve (a) of Fig. 12 shows the voltage required for the machine to run at maximum efficiency at constant torque. The variation is not excessive and the machine exhibits a close approximation to a 'constant torque at constant voltage' characteristic over this range, i.e. power proportional to speed. From 175 to 350 r.p.m. the efficiency falls as the speed is reduced.

The efficiency is about 50% over the range of speeds between 350 and 700 r.p.m. This rather low value can be ascribed to a considerable extent to excessive copper and iron losses, and it can confidently be expected that a redesigned machine in which these losses are reduced will yield much better efficiency. The efficiency falls off severely at the low-speed end, owing to at least two causes. First, the stator has 72 slots, so that at a synchronous speed of 175 r.p.m. there is less than 1 slot per pole per phase. Secondly, at the angle setting of −200° only 3¾ poles of the original 6 are still operative, the remainder having 'disappeared' by overlapping the wrong end of the transformer secondary.

The speeds plotted lie rather randomly above and below the

mean line. This is due to the fact that the efficiency/ speed curve has a rather flat maximum, and the methods used did not permit of its accurate determination.

In these curves only certain speeds are represented by plotted points, but it should be recorded that speed variation is in fact continuous, in that any desired speed can be obtained at any load within the capability of the machine by appropriate adjustment of primary angle.

(8) FURTHER SPEED/TORQUE CURVES

Fig. 13 shows the results of a test taken at the aligned setting of the transformer primary with four poles connected. The results are plotted for constant supply voltage. The peak efficiency of about 50% occurs at approximately 20% slip. The torque characteristic shows that the motor is free from crawling torques or other vices. Curve (c) shows the intake minus $T\omega_s$, and curves (d) and (e) show estimated stator copper and iron losses of the motor stator and transformer. Curve (f) shows the difference between curve (c) and the sum of (d) and (e). This curve presumably represents additional loss due to the unorthodox nature of the machine. Various sources of additional loss have been described in earlier papers[5,6] and the magnitude of curve (f) is consistent with expectation. They will not be discussed further here, since the purpose of the paper, which is to introduce this new type of machine, has already been served by this first experimental model. In a later machine iron and copper losses will be reduced, and the residue will then be more accurately determinable.

(9) CONCLUSIONS

The first experimental machine has shown that the principle of phase stretching may be applied successfully to control the speed of an induction motor, provided that the latter has a break in its stator winding which allows the flux through any rotor tooth largely to be destroyed once per revolution. The induction-motor part of the machine is thus subject to the limitations imposed by 'short stator' working as outlined in Reference 5, which shows that for high efficiencies the number of stator poles must exceed four. In spherical motors, to which Reference 5 specifically relates, the stator is essentially divided into two blocks, so that at least four poles per block are required at the top speed, imposing a top speed limit of about 400 r.p.m.

In the logarithmic motor almost the whole of the stator periphery is available for use as a single block, and the potential top speed is doubled.

The first experimental machine had a poor efficiency, largely because the potential speed range chosen was high. This resulted in small pole pitches in the primary winding, with the attendant high value of magnetizing current.

Development is continuing with a view to formulating design criteria for this type of machine.

(10) ACKNOWLEDGMENTS

The authors' thanks are due to A.E.I (Manchester) Ltd., Motor and Control Gear Division, for supplying the necessary stampings in three days, and to Mr. A. Gledson for constructing the machine in two months.

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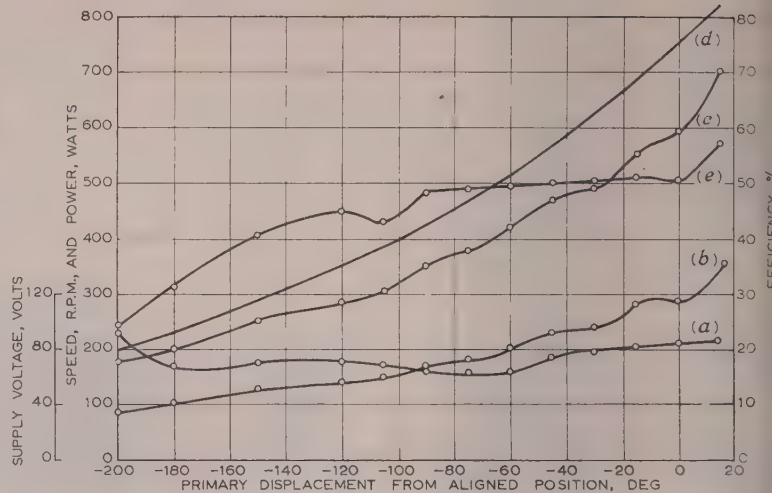
Fig. 12.—Load tests with variable speed (6-pole primary).
(a) Supply voltage.   (d) Calculated synchronous speed.
(b) Output power.   (e) Efficiency.
(c) Speed for maximum efficiency.
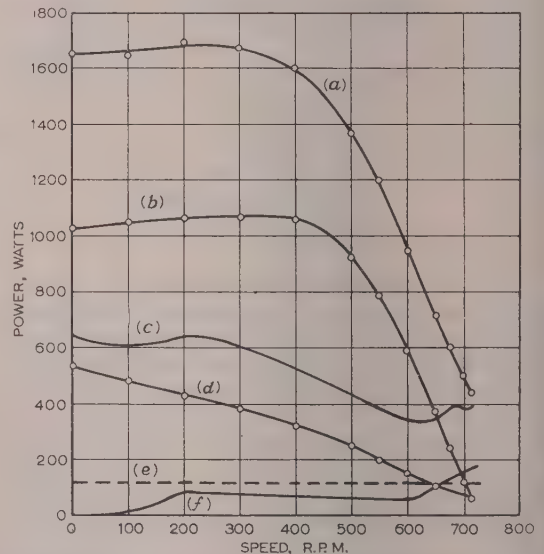
Fig. 13.—Brake test with primary and secondary aligned.
Short-circuited bars producing short-stator effect.
Constant voltage, 100 volts.
(a) Intake.   (d) Estimated copper loss.
(b) Synchronous power.   (e) Estimated iron loss.
(c) = (a)–(b).   (f) Unaccounted loss = (c)–(d)–(e).

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(12) APPENDICES

(12.1) Theory of the Logmotor

In Fig. 14, distances along the transformer primary winding are represented along the line AA'. Distances y along the

Fig. 14.—Geometrical representation of a logmotor.

secondary are measured along BB', and distances x along the motor stator along CC'. The line ABC is taken as the origin for distances measured along BB' and CC'. The origin of the primary is at O and is movable relative to B and C.

When O is opposite a point P on the secondary, where BP $= y_0$, the primary phase at A is $f(y - y_0) = \phi$, the function depending on the winding arrangement of the primary. Points such as P' on the transformer secondary are connected to points such as Q' on the stator, according to the relationship

$$x_{Q'} = g(y_{P'})$$

The rate of change of phase which occurs on the stator is then

$$\frac{d\phi}{dx} = \frac{d\phi}{dy}\frac{dy}{dx} = \frac{f'(y - y_0)}{g'(y)}$$

which may be written $d\phi/dx = a(y_0)$, since the phase rate must depend only on the displacement y_0 and be constant for any given value of y_0. Thus

$$f'(y - y_0) = a(y_0)g'(y) \quad . \quad . \quad . \quad . \quad (1)$$

Integrating $\qquad f(y - y_0) = a(y_0)g(y) + h(y_0)$

where $h(y_0)$ is the constant of integration.

Since

$$\frac{\partial}{\partial y_0}f(y - y_0) = -\frac{\partial}{\partial y}f(y - y_0)$$

$$a(y_0)g'(y) = -a'(y_0)g(y) - h'(y_0)$$

or

$$g'(y) + \frac{a'(y_0)}{a(y_0)}g(y) = \frac{h'(y_0)}{a(y_0)}$$

Integrating

$$g(y) = \exp -y\frac{a'(y_0)}{a(y_0)}\left[\int -\frac{h'(y_0)}{a(y_0)}\exp\frac{a'(y_0)}{a(y_0)}y\,dy + k(y_0)\right]$$

$$= \frac{h'(y_0)}{a'(y_0)} + k(y_0)\exp -\frac{a'(y_0)}{a(y_0)}y$$

$k(y_0)$ being the constant of integration.

$g(y)$ must not be a function of y_0 since the interconnectors remain fixed as the primary is moved.

$$h'(y_0) = -x_0a'(y_0), \text{ where } x_0 \text{ is a constant.}$$
$$a'(y_0) = \lambda a(y_0), \text{ where } \lambda \text{ is a constant.}$$

Therefore $a(y_0) = A\varepsilon^{\lambda y_0}$, where A is a constant.

$$k(y_0) = -\alpha, \text{ where } \alpha \text{ is a constant.}$$

Then $\qquad g(y) = x = x_0 - \alpha\varepsilon^{-\lambda y}$

and $\qquad h(y_0) = -x_0A\varepsilon^{\lambda y_0} + \Phi_0$, where Φ_0 is a constant.

Thus $\qquad \phi = f(y - y_0) = a(y_0)g(y) + h(y_0)$
$$= A\varepsilon^{\lambda y_0}(x_0 - \alpha\varepsilon^{-\lambda y}) - x_0A\varepsilon^{\lambda y} + \Phi_0$$
$$= \Phi\varepsilon^{-\lambda(y - y_0)} + \Phi_0, \text{ say}$$

Now $\qquad \varepsilon^{-\lambda y} = \frac{x_0 - x}{\alpha} \quad . \quad . \quad . \quad . \quad . \quad (2)$

and therefore

$$\phi = \Phi\frac{(x_0 - x)}{\alpha}\varepsilon^{\lambda y_0} + \Phi_0$$

If ϕ is a phase lead, then all quantities vary as $\varepsilon^{j(\omega t + \phi)}$. Constant phase along CC' appears to an observer, who moves a distance δx in time δt, such that $\omega\delta t + \frac{d\phi}{dx}\delta x = 0$

or $\qquad \frac{dx}{dt} = -\frac{\omega}{d\phi/dx} = u_x$, say

and $\qquad u_x = \frac{\omega\alpha}{\Phi}\varepsilon^{-\lambda y_0}$

Similarly $\qquad u_y = -\frac{\omega}{\partial\phi/\partial y} = \frac{\omega}{\lambda\Phi}\varepsilon^{\lambda(y - y_0)}$

(12.2) Current Density

It is considered desirable to have a constant surface current density J_s in the stator of the motor. The current contained within a length δx on the motor stator, $J_s\delta x$, is distributed in length δy in the transformer secondary.

Fig. 15 illustrates this by imagining the extremities of the lengths δx and δy to be joined by two of the interconnecting bars. Thus the current density necessary in the transformer

Fig. 15.—Current transference by interconnector.

secondary is $J_s\delta x/\delta y$, where δx and δy are related by eqn. (2) of Section 12.1. Thus $x_0 - x = \alpha\varepsilon^{-\lambda y}$ and $dx/dy = \alpha\lambda\varepsilon^{-\lambda y}$ whence the transformer current density, J_T, is $J_s\alpha\lambda\varepsilon^{-\lambda y}$.

[The discussion on the above paper will be found on page 108.]

BRUSHLESS VARIABLE-SPEED INDUCTION MOTORS USING PHASE-SHIFT CONTROL

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SUMMARY

The paper describes a method of 'pole-stretching' for induction machines in which part of the stator windings are fed directly from the mains supply and part from phase-shifting transformers. Variation of the angle of phase-shift enables continuous speed control to be effected. An experimental machine is described, the test results from which demonstrate that speed control with constant efficiency can be obtained over a speed range of 1·5 : 1. The limitations on the range of such machines imposed by the necessary condition that the stator be discontinuous are discussed, and a method of extending the speed range is then described. Machines of this type may be designed to run with a number of discrete synchronous speeds, in which case no phase-shifting transformers are necessary and speed change is effected by external switches only. The historical link between this type of machine and the spherical motor is outlined.

(1) INTRODUCTION

A new type of brushless variable-speed induction motor, called the 'logmotor', is described in a separate paper.[1] This paper outlines a method of pole-stretching whereby the phase increment per slot of the stator current may be changed in order

to change the synchronous speed of the travelling field. The current in each slot of the motor stator is supplied along a separate lead from a special type of transformer. A cylindrical machine such as the logmotor, whose synchronous speed is capable of continuous variation, must necessarily have an arc

of the stator which is not energized (see Section 7 of Reference 1). The present paper is concerned with an alternative method of changing the phase increment per slot, which leads to the development of a type of cylindrical brushless variable-speed induction motor quite different from the logmotor.

(2) THE PRINCIPLE OF PHASE MIXING

Fig. 1 shows a section through the stator of the new induction motor; a sector has been removed for the reason just discussed. The stator slots contain three separate 3-phase windings A, B and C, the connections to which are shown in Fig. 2. Windings A and B are supplied from 1 : 1 phase-shifting transformers whose primary windings are in series with winding C, so that the current flowing in A and B is substantially of the same magnitude as that in C. The phase of the currents in A may be advanced or retarded by means of phase-shifter 1. Phase-shifter 2 is mechanically coupled to phase-shifter 1 in such a way that, when the latter is set to advance the phase of the current in A by an angle θ, phase-shifter 2 retards the current in B by the angle θ and vice versa.
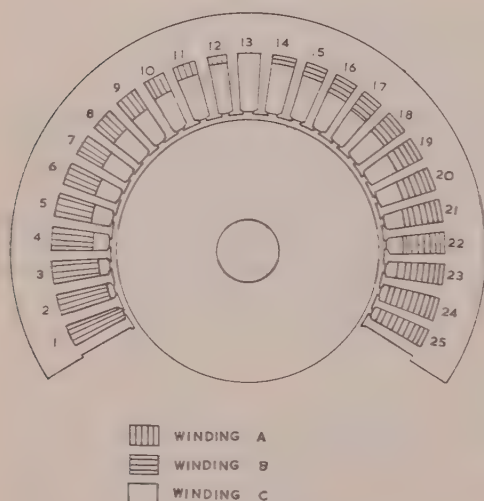
Fig. 1.—Arrangement of stator windings in a pole-stretching motor.
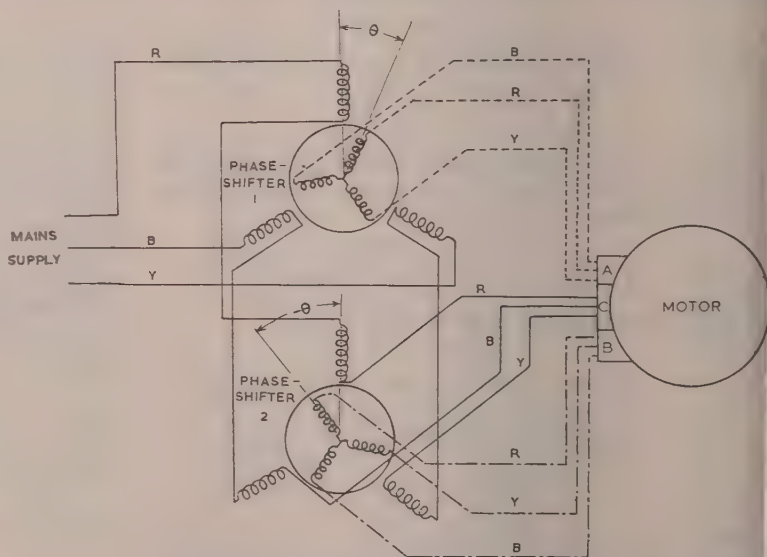
Fig. 2.—Connections between windings in a pole-stretching system.

Each of the windings A, B and C is arranged in the manner of a conventional 3-phase winding so as to produce phase progression around the periphery. The number of conductors of particular winding in each slot is graded as indicated by the shading, so that the magnitude of the stator current loading produced by any one winding varies around the periphery. The windings are so arranged that when both phase-shifters are se

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Fig. 3.—Vector diagrams for effective current
per stator slot.
(a) θ = 0.
(b) θ = 45°.
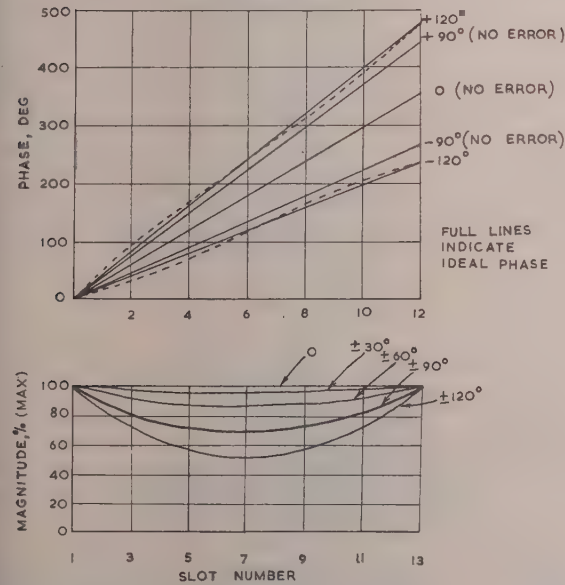
Fig. 4.—Phase and magnitude of effective current per slot obtained by
phase-mixing.
Full lines indicate ideal phase.

Fig. 5.—M.M.F. diagram for θ = 0.

if the windings shown in Fig. 1 are arranged to have two slots
per pole per phase, the vector diagram for the condition $\theta = 0$
is shown in Fig. 3(a); for the sake of clarity in the Figure, only
slots 8–18 are included. The contributions from winding C are
represented by the full lines Oa, Ob, Oc, . . ., etc., those from
winding A by the broken lines aA, bB, . . ., eE, and those from
winding B by the broken lines gG, . . ., 1L. The phase incre-
ment per slot is 30°. If now the phase-shifters are set to make
$\theta = 60°$, the vector diagram is modified to that shown in
Fig. 3(b). If the relative numbers of conductors in windings A,
B and C have been suitably chosen, the phase increment per slot
is increased uniformly. Since slot 25 in Fig. 1 contains only
conductors energized from phase-shifter 2, the phase angle of
the current in slot 25 has been advanced 60° and therefore the
phase increment per slot has been increased by 60/12 = 5°,
there being 12 slots containing winding B. Similarly, the phase
in slot 1 has been retarded by 60° so that the total phase angle
between slots 1 and 25 has been increased from 720° to 840°,
with the corresponding reduction in the angular velocity of the
field. Similarly, if the phase-shifters are moved through the
same angle in the opposite direction the total phase change will
be reduced from 720° to 600°. Thus variation in θ from $-60°$
to $+60°$ gives a speed range of 840/600 = 1·4.

If all the slots contain the same total number of conductors,
so that both the magnitude of the current per slot and the phase
increment are uniform for $\theta = 0$, and if for one value of θ (in
this case 60°) the phase increment is again uniform, the mag-
nitude is seen from Fig. 3 to be non-uniform. Furthermore,
for values of θ other than 0 and 60°, both the magnitude and the
phase increment will be non-uniform.

A machine may therefore be designed to have correct current
phase in all slots at one particular setting only. The greatest
discrepancy in magnitude occurs where the currents in two
windings are mixed in equal proportions, and a calculation of the
phase discrepancy is completed in Section 12.2; as an example
of the size of the errors introduced in a particular system, the
phase and magnitude values of the current per slot are computed
for the motor shown in Fig. 1. In this calculation, the conductor
ratios are chosen according to Section 12.1, so that the phase
increment is uniform for $\theta = 90°$. The calculated values of
magnitude and phase are compared with the ideal values in
Fig. 4. The phase errors for values of θ between 0 and 90° are
nowhere greater than 1·7°, and the maximum error for $\theta =$
$\pm 120°$ is less than 6°. Since a conventional 2 slot/pole/phase
winding, 2/3 chorded, has a phase error of 30° in alternate slots,
no problem is presented from purely phase considerations. The
magnitude errors are more serious. With the arrangement
described it is probably uneconomic in terms of stator copper
loss to increase θ beyond 90°, although some benefit might be

to $\theta = 0$ the effective stator-current distribution is identical with
that of a sector of a conventional induction motor. Accordingly,
the vectors which represent the effective slot currents are uni-
ormly phase-spaced by the appropriate amount. For example,

obtained by choosing conductor ratios which give uniform magnitude at $\theta = 60°$ rather than at $\theta = 0$. Furthermore, some magnitude error is clearly tolerable, for a conventional winding with 2 slots/pole/phase, 5/6 chorded, has a 14% difference in magnitude between currents in adjacent slots.

Fig. 5 shows the m.m.f. pattern obtained from a motor wound in accordance with Fig. 1 and having 2 slots/pole/phase and 5/6 chording, at one particular instant in time. In this Figure the phase-shifters are set to the zero position, and since this corresponds to a conventional winding in the same slots, only the resultant m.m.f. is shown. Fig. 6 shows how the resultant m.m.f. waveform [curve (f)] is built up from the components supplied by the three mains windings [curves (a), (b) and (c)] and the two sets of phase-shifter-fed windings. The instant of time chosen is when the red phase of the mains winding is at a maximum and the diagram refers to a phase shift of 90°. The centre slot contains the red phase only. It will thus be noted that the contribution from the red phase of either phase-shifter is zero, and this simplifies the illustration. It will be appreciated that the m.m.f. for other instants of time could also be synthesized. The increase in pole pitch between Fig. 6(f) and Fig. 5 is clearly indicated.

(3) SHORT-STATOR EFFECT

The phase-shift-controlled motor, like the logmotor[1] and the spherical motor,[2] is a short-stator machine which manages to achieve synchronous speeds corresponding to non-integral pole numbers by providing a section or zone of the periphery over which the rotor flux can decay to a low value before re-entering the active zone of the stator. The behaviour of short-stator machines has been investigated in some detail.[2,3] Their efficiency cannot exceed $n/(n+1)$, where n is the number of effective poles around the active zone. The output cannot exceed n times the rotor copper loss. Accordingly, it is usually uneconomic to design machines in which n falls below 4 at any setting. Earlier work[3] has shown that an inactive zone of about 90° is necessary to avoid undesirable 'carry over' of flux, so that the top speed of both the phase-mixing motor and the logmotor for 50 c/s operation is limited to about 1 000 r.p.m. for reasonable efficiency and power/weight ratio. For variation of θ between $-120°$ and $+120°$ the total phase change from end to end of the active zone is $\pm240°$, which means that $1\frac{1}{3}$ poles can be added to or subtracted from the number of poles on the winding C (Fig. 1). For n to remain greater than 4 at top speed, winding C should contain $5\frac{1}{3}$ poles, so that the speed range is $6\frac{2}{3}/4 = 1\frac{2}{3}$.

(4) EXPERIMENTAL PHASE-MIXING MOTOR

The first machine built was designed to have six poles for zero phase-shift on the grounds of rather better theoretical efficiency.

MMF, ARBITRARY SCALE

DISTANCE ALONG BLOCK
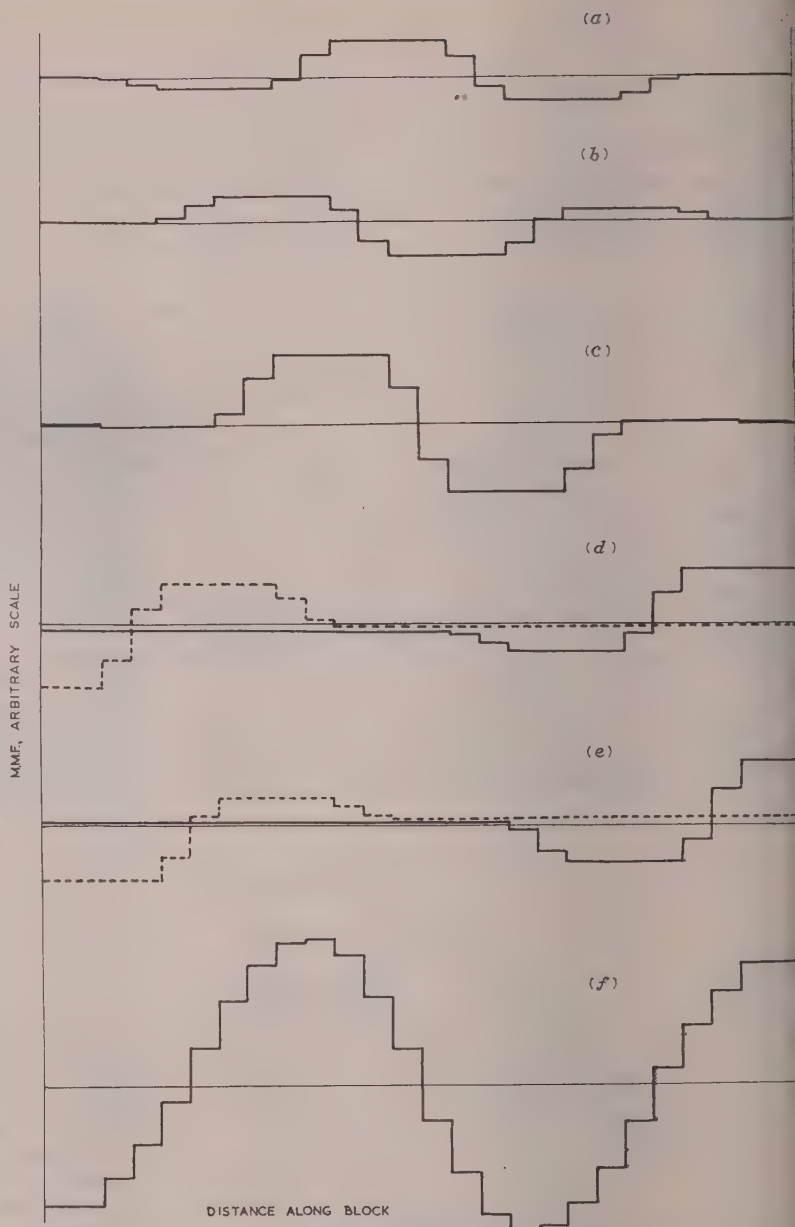
Fig. 6.—M.M.F. diagram for $\theta = 90°$.

(a) Contribution from mains winding (blue phase).
(b) Contribution from mains winding (yellow phase).
(c) Contribution from mains winding (red phase).
(d) ——— Contribution from phase-shifter 2 (blue phase).
　　　－－－－ Contribution from phase-shifter 1 (blue phase).
(e) ——— Contribution from phase-shifter 2 (yellow phase).
　　　－－－－ Contribution from phase-shifter 1 (yellow phase).
(f) Sum of the components (a)–(e).

To ensure that no carry-over of flux made analysis of the result difficult, a 120° arc was cut away from the stator. The remaining 240° had 45 slots. The rotor was 13 in in diameter and had 54 slots and the core length was 4 in. Initial tests were made to establish the nature of the flux distribution in the air-gap on open-circuit for the 5-, 6- and 7-pole settings. The flux distribution at particular instants of time may be plotted by feeding direct currents of the appropriate values into the three winding to correspond with one instant of the cycle and measuring th

ux across the block with a search coil and uxmeter. For this test the rotor was re-aced by a laminated iron cylinder con-ining no slots. Shturman[4] measured flux stributions in short-stator machines by using is technique on a tubular structure with no ssociated iron. When iron is present the chnique is difficult to apply, because of the ect of residual magnetism. The method as extended by feeding alternating currents to the 3-phase windings, the relative values the three currents being appropriate to one stant of the cycle. Flux measurements can en be made with a search coil and volt-eter. The experimental results are shown in g. 7. The areas above and below the axis e seen to be equal in each case at all instants time, indicating that there is no shaft flux d that an appropriate pulsating flux occurs the case of odd numbers of poles. The sults demonstrate clearly that the technique phase mixing enables pole-stretching to be fected.

The next experiment consisted of load tests constant current with both even and odd umbers of poles, and the results are shown Figs. 8 and 9. The difference between the take-less-stator copper loss and the syn-ronous power is shown in curve (d) in ch case. Curve (e) on each Figure shows e iron loss. These iron-loss curves were omputed by measuring the flux density at any points along the gap from which the ensity in the yoke was estimated and cal-ulating the iron loss from known data for e type of stampings used. The crosses on igs. 8 and 9 are obtained by adding exit dge loss to the iron losses. The latter were alculated according to the method outlined Reference 3, estimating a value of rotor me-constant under the block from the ex-erimental characteristics and measuring e time-constant outside the block by bserving the decay of flux using a search il. Clearly there are very few unaccount-ble losses.

Fig. 10 shows constant-voltage torque/speed d efficiency curves for various angles of hase shift from −120° to +120°. These urves indicate that some undesirable effects ccur for θ = ±120°. The efficiency is lower both settings, while the speed/torque curve as a double peak at the top speed setting. hese effects could probably be reduced by esigning the winding to be correct at θ = 60° ather than at θ = 0. The results also show at a working speed range from 430 to 30r.p.m. is possible with the system de-ribed. The figures quoted refer to the motor ly. Overall efficiencies are not shown, since the phase-ifters used were not matched to the experimental machine d the phase-shifters were working at low load and therefore w efficiency. When well-matched, the estimated phase-ifter efficiency is 90%, and since about one-half of the tal power is fed directly to the motor, a reasonable estimate the overall efficiency is 62%.
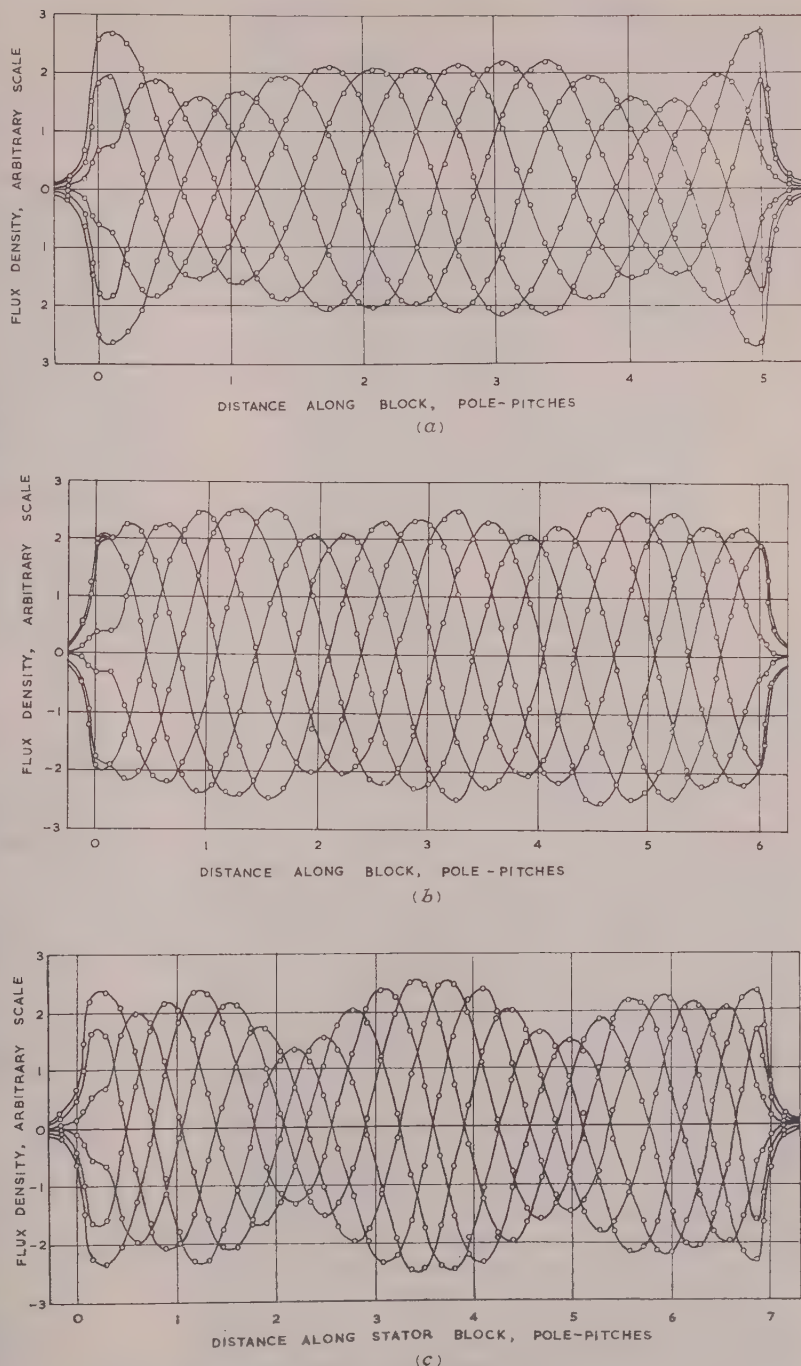
Fig. 7.—Open-circuit flux distribution under a multi-pole stator block.
(a) 5-pole.   (b) 6-pole.   (c) 7-pole.

(5) EXTENSION OF THE SPEED RANGE

The speed range may theoretically be extended indefinitely without reducing the minimum number of poles on the stator block and without mixing currents which are more than 90° apart by the use of the technique illustrated in Fig. 11. The stator winding of the machine described in Section 4 is repre-sented in this Figure by the rectangle BB′b′b. The proportion
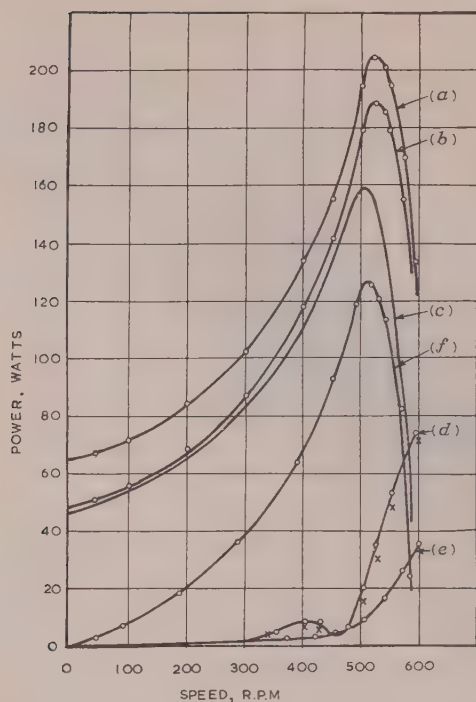
Fig. 8.—Brake test results for a 6-pole stator block ($\theta = 0$).

 (a) Intake.
 (b) Intake less stator I^2R loss.
 (c) Synchronous power.
 (d) (b)–(c).
 (e) Calculated iron loss.
 (f) Output.

Fig. 9.—Brake test results for a 7-pole stator block ($\theta = 90°$).

 (a) Intake.
 (b) Intake less stator I^2R loss.
 (c) Synchronous power.
 (d) (b)–(c).
 (e) Calculated iron loss.
 (f) Output.
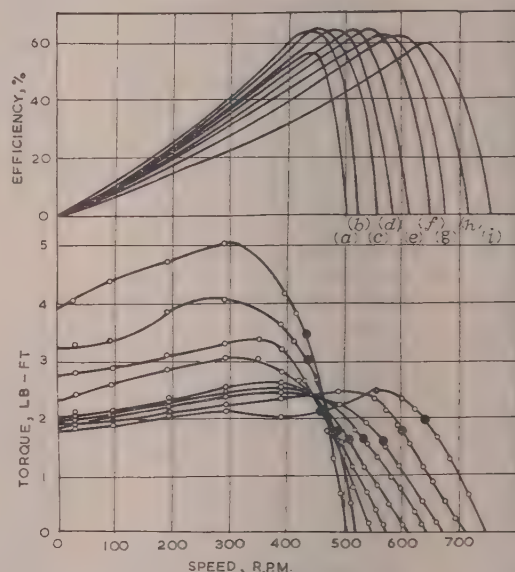
Fig. 10.—Torque/speed and efficiency curves for various angles of phase-shift.

 (a) $\theta = 120°$. (f) $\theta = -30°$.
 (b) $\theta = 90°$. (g) $\theta = -60°$.
 (c) $\theta = 60°$. (h) $\theta = -90°$.
 (d) $\theta = 30°$. (i) $\theta = -120°$.
 (e) $\theta = 0°$.

  ● = Full-load points.

of mains-fed coils in any slot in a section such as ABB′A′ does not decrease linearly with the distance of the slot from AA′ (see Section 12), although it is a fairly close approximation to a linear relationship and it may conveniently be so represented in a schematic such as Fig. 11. If two additional phase-shifters are employed they may be connected respectively to the first pair of phase-shifters through 2 : 1 gearing, such that when the phase-shifter supplying slots in section ABB′A′ is set to give a phase shift of θ, the phase-shifter which is geared to it gives a phase shift of 2θ. When four phase-shifters are used the whole of the stator periphery is arranged to correspond with section CC′c′c of Fig. 11. Examination of the Figure will show that there are slots which mix currents of zero phase-shift (mains fed) and phase-shift θ (section ABB′A) and there are also slots mixing currents of phase-shift θ with currents of phase-shift 2θ (section CC′B′B), but no slots carrying currents of both zero and 2θ phase-shift. A similar situation obtains to the left of AA′ with $-\theta$ and -2θ phase-shift. The maximum value of θ without undue loss of effective m.m.f. may still be 90°. However, the extreme slots at CC′ and cc′ contain 100% of conductors with phase-shifts of 180° and −180° respectively, which means that two poles can be added to the block by a phase-shift in one direction only. Reversal of the phase-shift will therefore sub-

Fig. 11.—Schematic of a motor stator with multiple phase-shift windings.

act two poles. Hence a stator can be wound to give a 6-pole configuration with zero phase-shift, so that it becomes a 4-pole and an 8-pole device in the extreme positions. Thus a 2 : 1 speed range is obtained with a minimum pole number of four. Without the additional phase-shifters this speed range could be obtained only by reducing the number of poles to two at the top speed setting.

The system shown in Fig. 11 is clearly extendible indefinitely in both directions by the use of more phase-shifters. The use of many phase-shifters is not attractive economically, for two reasons. First, as the number of phase-shifters increases, the fraction of the motor which each supplies becomes smaller and the rating of the phase-shifter is lower for a given size of motor; small phase-shifters, like any other a.c. machine, become less efficient and have a lower power/weight ratio. Secondly, the greater the speed range, the greater is the number of poles at bottom speed, for the top speed is limited to, say, a 4-pole stator block; as the number of poles increases, the magnetizing current may become excessive. The first of these limitations is not so serious as the second, since the phase-shifters may be 2-pole machines.

It was considered well worth while, however, to develop a system using four phase-shifters and the same top speed as in the first machine, since 2 : 1 is a much more useful speed range than the 1·5 : 1 obtainable with only two phase-shifters. To this end a scheme was developed for producing currents of phase-shift angles θ and 2θ from one machine, and such a system will now be described.

(5.1) The θ–2θ Phase-Shifter

A developed diagram of one phase of the stator and rotor windings is shown in Fig. 12. Both stator and rotor carry two windings such that the pitch of one is twice that of the other. There is no coupling between the two windings on either member, between the large-pitch stator winding S_1 and the small-pitch rotor winding R_2, and between S_2 and R_1. The only windings which are mutually coupled are S_1 and R_1 and S_2 and R_2. Windings S_1 and S_2 are in series. If the rotor be displaced from the position shown in Fig. 12 so as to produce current of phase-
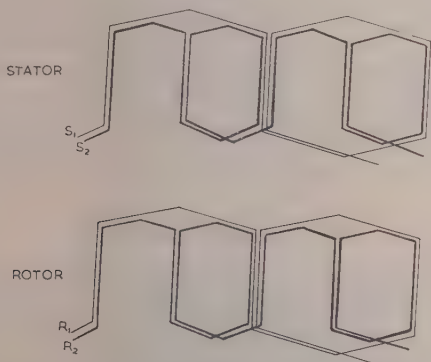
Fig. 12.—Developed diagram of stator and rotor windings of a double phase-shifter.

shift θ in R_1, then the current in R_2 must be shifted 2θ and R_1 and R_2 can be used to feed sections $AB'C$ and $B'CC'$ respectively (Fig. 11). A second similar machine can be used to supply currents of phase-shift $-\theta$ and -2θ. The primaries of the two phase-shifting machines and the mains-fed coils are all in series.

A linear version of the θ–2θ phase-shifter was constructed to measure the effective coupling between the four windings when all four were chorded. The large-pitch coils constituted a

2 slot/pole/phase system, so that the small-pitch coils provided a 1 slot/pole/phase winding. Each winding was short-chorded by one-third of a pole pitch. The device was found to operate satisfactorily, cross-coupling being less than 1%. A new experimental machine using this type of phase-shifter is now in process of construction.

(6) PROPERTIES OF PHASE-MIXING MACHINES

The pole-stretching motor described here has several features in common with those of the logmotor described in Reference 1, both being examples of the more generalized type of pole-stretching arrangement shown in Fig. 13. Machine A is a device
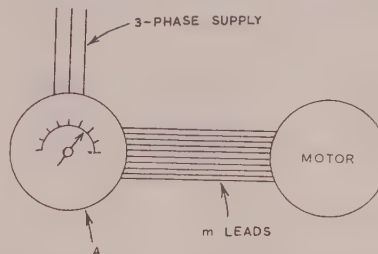
Fig. 13.—The generalized pole-stretching machine.

which takes in power from a 3-phase supply and redistributes it into m leads which feed the motor. The arrangement within the machine A and the motor are such that, when the position of the control handle on A is changed, all the pole pitches of the stator-current distribution on the motor are changed by the same amount, yielding a uniform-velocity field of a different value.

In the arrangement described here, phase mixing is performed in the motor itself as well as in machine A, which in this case consists of the two phase-shifters. If these are of the θ–2θ type there are 15 leads between A and the motor. If only single phase-shift control is used, there are nine interconnecting leads. In the logmotor with uniform slotting, phase mixing is performed in machine A and there are almost as many leads between A and the motor as there are stator slots. This difference between the principles of the types of machine results in a difference in the method of manufacture. To minimize the copper losses in the interconnecting leads the logmotor is constructed as a unit so that the interconnectors are as short as possible. The phase-mixer motor is designed to be controlled from a remote point. In this case the power/weight ratio of the motor alone is high, being of the order of 25 watts/lb. Each of the phase-shifters in the 10 h.p. experimental machine is called upon to handle a maximum of 3 kW. In the case of the logmotor the whole of the motor power is handled by the control machine. A phase-mixing motor fed from a pair of single phase-shifters obtains approximately half of its power directly from the mains; if it is fed from double phase-shifters about three-quarters of the total power is handled by the control. The power/weight ratio of the phase-mixing motor and its control is therefore theoretically higher than that of the logmotor, but the logmotor clearly has a superior speed range. Extension of the speed range of a phase mixer beyond 2 : 1 would be uneconomical, because of the complication of the extra phase-shifters, whereas the logmotor range is extendible merely by the rearrangement of the primary winding and interconnectors. Furthermore, when the logmotor is used as a 'vary arc' machine, the torque increases with the speed, whereas the phase-mixing machine is virtually a constant-power device when run at maximum efficiency.

(7) A NEW FORM OF POLE-CHANGING MOTOR

An interesting by-product of the continuously-variable-speed phase-mixing motor is a machine which provides a limited number of discrete speeds, and for which the control system A of Fig. 13 consists only of a set of switches. An example of the connections for this type of machine is shown in Fig. 14. The motor is wound according to the arrangement shown as BB'b'b of Fig. 11. The three sets of coils normally fed from the mains and the phase-shifters 1 and 2 are designated C, A and B respectively. The arrangement shown in Fig. 14(a) gives the
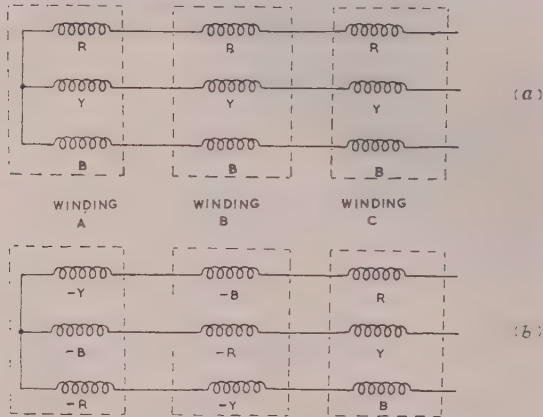
Fig. 14.—Winding connections for pole-changing machine.
(a) Zero phase-shift.
(b) Effective phase-shift of 60°.

effect of zero phase-shift. Reconnection as in Fig. 14(b) produces the same effect as a phase-shift of 60°. If the roles of A and B are interchanged, an effective phase shift of −60° is obtained. The method is applicable to systems having effectively any number of phase-shifters.

Effective phase-shifts of ±90° and ±30° can be produced at the expense of a standard 3-phase transformer which enables star-delta switching to be used.

(8) THE LINK BETWEEN ANGLED-FIELD MOTORS AND POLE-STRETCHING MACHINES

The principle on which the spherical motor is based[2,3] is that a rotor is arranged so that points on its surface are constrained to move at an angle to the direction of motion of the travelling field set up by the stator. Variation of speed is achieved by mechanically changing the angle between the lines of action of the field and the rotor. This necessitates the use of a rotor and stator whose surfaces are parts of concentric spheres, so that a uniform air-gap can be maintained as the one is moved relative to the other. It is mentioned at the end of the first paper on this machine that a cylindrical version of the angled-field machine can be made in which the necessary adjustment in angle is simulated by using a fixed mechanical structure and phase-shifting transformers.

The principle of such a machine is shown in Fig. 15. The stator of the motor is divided into strips as shown, so that in the first instance relative movement between adjacent strips is possible. Figs. 15(a) and (b) show two possible configurations.

The resulting field from a stator arrangement such as that in Fig. 15(a) travels in the direction θ_1 to the strips at velocity $u_1 = 2p_1 f$. A rotor constrained to move in the direction AB has an effective synchronous speed $u_1/\cos \theta_1 = 2p_1 f/\cos \theta_1$. If the stator strips are reset to the position shown in Fig. 15(b),
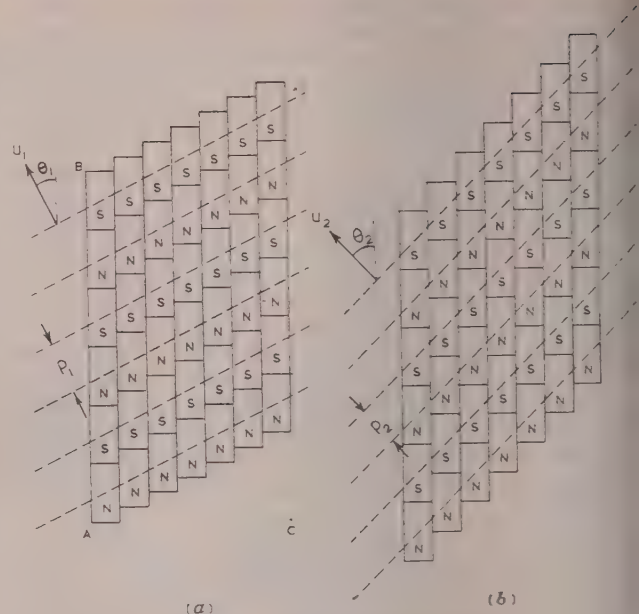
Fig. 15.—The angled-field principle.
(a) Pole pitch p_1, angle θ_1.
(b) Pole pitch p_2, angle θ_2.

the angle between the directions of the field and the rotor is increased to θ_2, suggesting a higher synchronous speed.

However, reference to Fig. 15 shows that the pole pitch p_2 is smaller than p_1; in fact, $p_2/\cos \theta_2 = p_1/\cos \theta_1$, so that the synchronous speed for the configuration in Fig. 15(b) is

$$\frac{u_2}{\cos \theta_2} = \frac{2p_2 f}{\cos \theta_2} = \frac{2p_1 f}{\cos \theta_1}$$

i.e. there is no change in synchronous speed.

This result may also be obtained by observing the rate at which a point on the rotor crosses the poles of the system whatever their configuration, provided it is assumed that the rotor can conduct equally in all directions—which is a requirement for the exploitation of the angled-field principle.

The important aspect of Fig. 15, however, is that a rotor constrained to move parallel to the direction AC has a synchronous speed $u_1/\sin \theta_1 = 2p_1 f/\sin \theta_1$ in the case of Fig. 15(a) and of

$$\frac{u_2}{\sin \theta_2} = \frac{2p_2 f}{\sin \theta_2} = \frac{2p_1 f \cos \theta_2}{\cos \theta_1 \sin \theta_2}$$

in the case of Fig. 15(b), so that variation of speed is achieved.

The next step is to replace the mechanical displacement of the stator strips by an apparent displacement due to a change of phase of the stator current in the different strips, the method being illustrated in Fig. 16. In this example the stator is divided into six strips AA', BB', . . ., FF', each of which is wound with a conventional 2-pole winding so as to produce a travelling field along AA', etc. The squares on the Figure are used to represent phase groups. An array such as Fig. 16(a) produces a field travelling at an angle of 45° to AA'. According to the principle outlined with reference to Fig. 15, the rotor must be constrained to move parallel to AF, and it is apparent from Fig. 16(a) that each point on the rotor will traverse two pole pitches as it crosses the block. The supplies to the various strips are now phase-shifted by various amounts as shown in Fig. 16(b), yielding the

Fig. 16.—An angled-field motor using phase-shift techniques.

(a) Condition for zero phase-shift.
(b) Phase-shift applied.

four poles around the periphery, while a shift of $-90°$ produced two poles in 360°. The machine was found to have excellent characteristics at both these settings, but was incapable of stable running at any speed between the two for the reasons given in Section 1.

The departure from the angled-field principle to the pole-stretching principle involves only one fundamental change. With the method of construction shown in Fig. 17, the windings on each strip may be arranged so that an even number of poles may be contained within the axial length. It would appear that any number of poles may be contained around the periphery of the active arc with such an arrangement, since each N-pole has its opposite S-pole alongside it axially. With the arrangement in which conventional stator punchings are used with axial slots and with a segment removed, there is no axial flux and the net flux crossing the air-gap should be zero. The effects of this limitation on the air-gap flux were investigated before the method was accepted. One of the attractive features of the conventional method of construction is that a conventional squirrel-cage rotor may be used, and no additional conducting peripheral rings are required.

(9) CONCLUSIONS

The principle of the phase-mixing motor has been demonstrated and the limitations of the system are fairly clear. The motor itself is essentially a short-stator machine whose output is limited theoretically to n times the rotor copper loss for n poles on the stator. This limitation on the choice of pole numbers determines the speed range of practical machines. The facility of being able to control the motor by means of auxiliary apparatus situated at a distance is valuable for many applications. The characteristics appear suited to constant power, as are those of spherical motors, although the power/weight ratio of the whole system may be lower than that of a spherical motor of the same output. The mechanical construction is conventional, except for the removal of an arc of the motor stator. Experiments with machines in which a short-circuited section of stator is used instead of removing the arc are continuing with a view to making the construction entirely conventional. The winding arrangements on both motor and phase-shifters are conventional, apart from the graded number of turns. The design of this type of machine consists of two parts—first the design of a short-stator machine and secondly the design of conventional phase-shifters to match the impedance of that machine.

...ase pattern shown, which produces a field travelling at a ...eater angle to AA′. The new synchronous speed can easily be ...etermined by noting that a point on the rotor now traverses ...ur pole pitches in crossing the block. The two conditions ...own in Figs. 16(a) and (b) provide two speeds, the second of ...hich is exactly half the first. Clearly any intermediate speed ... possible by suitable choice of phase-shift. The boundaries ...tween the strips are effectively the slots of the machine so far ..., a point on the rotor is concerned, and it is clear that if the ...mber of effective slots per pole is to be reasonable, a large ...mber of strips is required, each one demanding its own phase ...ift. It was for this reason that the method of phase mixing ...as first applied to this problem to remove the necessity for ...large number of phase-shifters.

...An experimental machine was constructed using six blocks ...ranged around the entire periphery of the rotor as shown in ...g. 17. The slots on each block were pre-skewed at 45° and

Fig. 17.—Mechanical layout of a helical-field motor.

...ranged to form continuous helices, and the windings were ...ranged so that a point on the rotor crossed three pole pitches ... one revolution for $\theta = 0$. A phase-shift of $+90°$ yielded

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(2) WILLIAMS, F. C., LAITHWAITE, E. R., and PIGGOTT, L. S.: 'Brushless Variable-Speed Induction Motors', *ibid.*, Paper No. 2097 U, June, 1956 (**104** A, p. 102).

(3) WILLIAMS, F. C., LAITHWAITE, E. R., and EASTHAM, J. F.: 'Development and Design of Spherical Induction Motors', *ibid.*, Paper No. 3036 U, December, 1959 (**106** A, p. 471).

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(12) APPENDICES

(12.1) Proportion of Turns used in Phase Mixing

The system is designed to give a uniform phase increment per slot when the phase-shifters are set to 90°. In Fig. 18(a), which
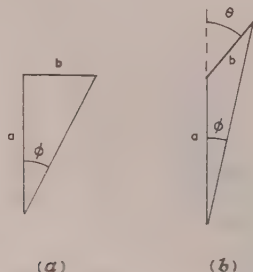
Fig. 18.—Illustrating the problem of phase error.

(a) rth slot of a system for θ = 90°.
(b) Condition with phase-shift angle of θ.

shows the vector diagram for the rth slot of a system having S slots in each half, it is assumed that each slot contains the same total number of conductors, N, and thus

$$a + b = N \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\tan 90° \frac{r}{S} = \frac{b}{a} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Hence

$$\frac{b}{N - b} = \tan \frac{90°r}{S}$$

or

$$b = \frac{N}{1 + \dfrac{1}{\tan 90°r/S}} \quad . \quad . \quad . \quad (3$$

(12.2) Phase Errors when θ ≠ 90°

The vector diagram for a slot carrying currents differing in phase by an angle θ is shown in Fig. 18(b). Again, $a + b = N$ and

$$\tan \phi = \frac{b \sin \theta}{a + b \cos \theta} = \frac{b \sin \theta}{N - b + b \cos \theta}$$

The desired conditions are that when $\theta = 90°/x$, ϕ should equal ϕ_0/x where $\phi_0 = 90°r/S$. Thus the error is given by

$$\delta = \text{arc tan} \frac{b \sin 90°/x}{a + b \cos 90°/x} - \frac{\phi_0}{x}$$

Substituting for a and b from eqns. (1) and (3) gives

$$\delta = \text{arc tan} \frac{\tan \phi_0 \sin 90°/x}{1 + \tan \phi_0 \cos 90°/x} - \frac{\phi_0}{x} \quad . \quad . \quad (4$$

It can be seen that when $\phi_0 = 45°$ ($a = b$) the error is zero for all values of x, i.e. the middle slot of the phase-shift section is always correct. The maximum value of δ for all values of x between $1 \cdot 0$ and ∞ and all values of ϕ_0 between 0 and 90° has been computed and found to be $1 \cdot 67°$. The penalty for exceeding 90° phase-shift so far as slot phase error is concerned has been assessed by computing the maximum value of δ for all values of ϕ_0 from 0 to 90° and $x = \frac{3}{4}$, and this is found to be $5 \cdot 66°$.

DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE UTILIZATION SECTION, 10TH NOVEMBER, 1960

Mr. C. C. Inglis: Returning to electrical engineering after many years of work in other fields, I asked what had happened in the design of machines, to find that, apart from a very welcome improvement in general detail, technique of installation, finish, etc., nothing very fundamental had occurred. But three years ago our long-cherished belief that the speed of an a.c. machine depended on the number of poles (and that had to be even) was shattered, and now the authors talk about fractional numbers of poles, such as 5·2. The next thing which affects the speed of the motor is the frequency; no longer will the a.c. machine designer be able to set 50c/s on a slide-rule and work from there—he will have to set any figure between 1 and 100c/s and design his machine under those conditions.

The future therefore holds tremendous possibilities. Much will be achieved by the use of solid-state devices. A year ago workers on these devices were talking about 10kW controlled rectifiers, but today they are talking about 100kW; I am sure there will be a further tenfold increase before long.

One question of great importance to all those who deal with transport is reversal of rotation. I am not quite clear about what happens when one tries to reverse the variable-speed machine. Is the machine reversible, and, if so, does it work equally well in either direction?

The potentialities of a.c. electrification are tremendous, and I therefore welcome the authors' challenging of past concepts through the potentialities of variable-speed a.c. motors, which can be of the greatest importance in railway electrification.

Mr. A. F. M. Ashworth: The antecedent of these machines is the spherical motor, whose output must exceed 50hp if it is

not to have poor performance. Do the authors recommend any limit to the output of their new machines?

The experimental machines which have so far been built have been of comparatively low output and wound for low-voltage supply. This has demanded a large number of turns in each stator slot, which thus permits coils with differing numbers of turns around the periphery of the transformer in the logmotor and the graded mixing of phases in the phase-shift motor. Machines in the range 250–500hp, which are commonly l.v. devices, require two or fewer effective conductors per slot. It would therefore seem impossible to apply these new machines to such ratings.

Professor G. H. Rawcliffe: Prophecy is a dangerous exercise, but I think the phase-shifting motor is more likely to prove an industrial success than the logmotor. The principles of the two have much in common, but the phase-shifting motor can be constructed in semi-conventional form. There is much less physical and electrical 'hangover' about it. If the authors can devise means of dealing with this 'hangover', whereby the energy which is lost as each rotor element comes out of the stator field is made available as the element goes back into the field again, I think the phase-shifting motor has a chance of industrial success.

Further, the phase-shifting motor is easier to manufacture and has less waste iron than the logmotor: only part of the power has to go through the phase-shifter(s), whereas the whole power has to go through the 'slide-rule' in a logmotor. Both types of motor present the same difficulty in relation to the making and breaking of fields. If this is overcome, the advantages mentioned will, I believe, tell in favour of the phase-shifting motor.

strongly advise the authors to try to make this machine work
[ov]er a moderate speed range using one phase-shifter rather than
[ove]r a greater speed range with two. A little done simply is
[re]ally better than a lot done with much complication. I also
[rec]ommend the authors to publish all future test results with
[con]stant applied voltage; and not with constant current flow,
[wh]atever experiments may be performed at constant-current.
[Th]e real test of a machine must always be at constant voltage.
[I d]o not think the phase-shifters are 'conventional': they are
[cur]rent transformers and not voltage transformers, and it would
[be] interesting to know what voltage and power they absorb.

[I]n my view, the authors should avoid speaking of the phase
[err]or (as they call it) in conventional windings. Machines using
[the]se windings are highly successful; and, even if the authors'
[arg]uments were correct, I think it is dangerous to seek to justify
[the] shortcomings of a half-developed machine by reference to
[the] alleged defects of something else which is already widely
[acc]epted.

[W]hether or not either of the authors' machines will be used
[ind]ustrially remains to be seen; but they are much to be com-
[me]nded for helping to infuse vigour into electrical machine
[en]gineering, which has become very stereotyped.

Mr. J. S. Holmes: I should like to draw attention to work
[wh]ich has been done on short-stator machines by the aircraft
[ele]ctrical industry.

[A] design was carried out to assess the weight of a 400 c/s
[40]kVA spherical induction generator with a 2 : 1 input speed
[ran]ge and a 3-phase 208-volt output. The weight of this
[ma]chine, with a heat rejection of 2·5 watts/cm^2, was 300 lb.

[F]ig. A shows the output of a conventional aircraft salient-pole
[alt]ernator based on a frame size relative to 300 lb in weight,
[an]d the output is directly proportional to speed. For the short-
[sta]tor machine the output is theoretically inversely proportional
[to]the speed, as shown by the broken curve. This is not realized
[in]practice, since an increase in the number of poles approaches
[the] limiting pole pitch to which the authors refer and the actual
[cur]ve falls away in the manner illustrated.

[D]esign exercises were also carried out on the phase-mixer and
[a]machine of similar performance, and the calculated weight
[of]the former was 240 lb. This machine had a 2θ phase-change
[an]d required 160 lb of phase-shifting equipment. A log
[gen]erator was built and tested, its weight being 480 lb.

Mr. W. Hill: We have heard a good deal about the economic
[asp]ects of these new machines, and bets of 3 : 1 or 4 : 1 have
[bee]n mentioned. This leads me to make a suggestion which I
[am]sure the authors will not take amiss. Textbooks never
[me]ntion economic parameters, which we regard as just as
[imp]ortant as others, but I should like to think that engineers,
[wh]o are trained to deal with complicated subjects, would take
[the] economic side as just another subject in the syllabus.
[En]gineers like to deal with facts, and there are economic facts.
[Ca]n we not have some guidance on these? Can we not sit
[dow]n together and elicit the economic facts and determine what
[a m]achine will be worth?

Mr. R. D. Ball: These papers are of very great interest,
[esp]ecially since we find that the spherical motor, which is
[diff]icult to manufacture and expensive, is suddenly changed into
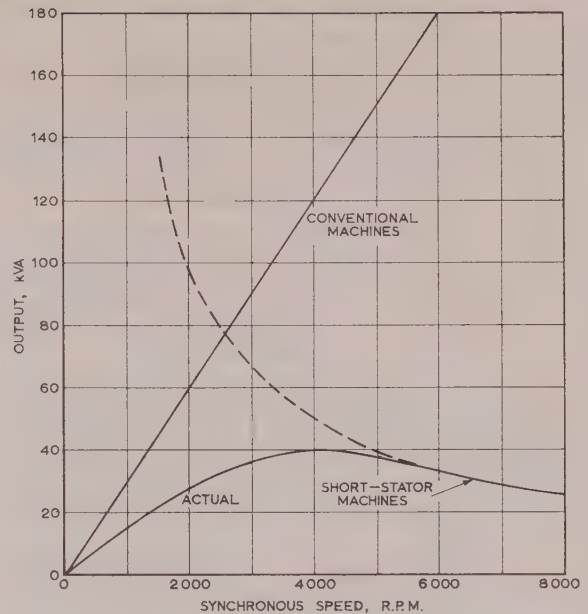
Fig. A.—Approximate output curves for 400 c/s machines with a fixed frame size.

a cylindrical-rotor machine, and with the logmotor and the
phase-shift pole-stretching motor comes into the practical
engineering field. I believe that if we made them large enough
and were content with low speeds, they would be extremely
efficient.

This advance over the last few years has brought out other
possibilities. I wonder whether the authors have considered a
hysteresis permanent-magnet-steel type of spherical or cylindrical
rotor, which might cut out the slip losses? At Manchester
University they have developed linear arrays, and it would
seem to be a possible scheme to have mains, $+\theta$ and $-\theta$ pole-
stretching windings on these arrays and use this device for
driving planers, since these require a linear motion. In such
an arrangement the rotor losses would be much reduced by
switching from pole-to-pole grouping and feeding back some
of the kinetic energy by induction-generator action into the
mains.

Dr. W. Fong: Will the authors indicate briefly the winding
arrangement for the phase-shifter motor, since it is not given in
the paper? It is stated in Section 5 that there are two disadvan-
tages in extending the speed range of this motor: the mains-fed
coils become a smaller proportion of the total, and the coils
fed through the phase-shifter become greater as the number of
phase-shifters increases. Would not this also be a disadvantage
in so far as the power flow through the phase-shifters would
become larger?

[The authors' reply to the above discussion will be found
overleaf.]

SOUTH-WEST SCOTLAND SUB-CENTRE, AT GLASGOW, 23RD MARCH, 1960*

Dr. A. J. Small: This motor is a further attempt to obtain a
[con]tinuously variable speed control of a cage-type induction
[mo]tor. Having obtained a speed range of 4 : 1 the authors
[cer]tainly demonstrate that the principle of phase stretching can
[be]successfully applied.

* Discussion on Paper No. 3149 U only (see page 91).

Since part of the stator of the machine requires to be left
unenergized for successful operation, full use is not being made
of all the available active material, and consequently it appears
that the machine will be more bulky than a conventional one
of the same output.

For the experimental motor the efficiency has a peak value of

63%, and only 50% over the limited speed range 750–350 r.p.m., i.e. about 2 : 1, and still lower at lower speeds. It would have been informative if results had been given of brake tests at fixed displacements of the primary from the aligned position, i.e. a demonstration of the variation of speed and efficiency as the load is varied at each displacement setting. Would increased rotor losses at lower speeds cause a marked departure from the approximate constant-speed characteristic of an induction motor?

In the Introduction the units of angular velocity, expressed as $2f/n$, are not stated, but are presumably revolutions per second instead of the usual radians per second. The unconventional use of n and p for the number of poles and the pole pitch respectively is somewhat confusing, particularly when p is almost universally adopted for the number of pole pairs.

I am pleased to hear that development of the design of this type of machine is continuing, since the machine clearly has characteristics which would ensure its application in situations where sliding brush contacts are prohibitive. I trust that as industrial techniques are applied to the construction of the machine the present difficulties as well as the losses will become progressively less.

Mr. H. E. Clapham: It would seem that the discontinuity effects are inseparable from machines employing pole- or phase-stretching techniques in order to obtain variable speed. Fig. 11 demonstrates the effects of discontinuity very clearly. To overcome these undesirable effects the authors had to provide a 'flux killing winding' on the motor stator, which leads to increas and concentrated losses. This situation could be a very gre obstacle on a machine of large output. The effects shown Fig. 11 were obtained on light load; would they be different the machine were on load?

The logmotor seems easier to construct than the spheri motor, although the provision of bearings between the tran former and the motor presents problems. Access to th bearings must be provided for assembly and maintenance, a this is made difficult by the multiplicity of winding connectior In view of this, is it not possible to use more than one conduct per slot on the stators and so make these connections lighte The two stator short-circuiting rings can be a potential source trouble, since fractures are likely to occur where the slot co ductors make a T-joint with the ring. Such troubles we once very common on squirrel-cage rotor windings, but tod are encountered only on poorly designed machines.

Since two air-gaps are involved one would expect the ma netizing current to be relatively large and the power fact low.

Although the demand for variable-speed drives has be largely met by the a.c. commutator motor, so far as this count is concerned, recent advances in germanium and silicon rectifi have caused d.c. motors and the Kramer-cascade system appear as competitors in this field. The logmotor has th appeared at a time when competition in variable-speed driv has already become more lively.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Professor F. C. Williams, Dr. E. R. Laithwaite and **Messrs. J. F. Eastham, L. S. Piggott** and **W. Farrer** (*in reply*): Both machines are capable of reversal by interchanging any two phases of the supply, as with a conventional induction motor. In the logmotor, however, the current loading varies around the periphery of the transformer. Short-stator effect produces non-uniform flux distribution around the air-gap, so that the log-motor has a preferred direction of rotation.

This same short-stator effect, which places a lower limit on the size of good machines in the case of the spherical motor, has precisely the same effect on both these machines, and we do not envisage either type being capable of good performance under 50 hp, except for very small speed ranges. It seems probable that the low-voltage machines in the range Mr. Ashworth quotes could not be designed as logmotors. The phase-shift type, however, contains phase-shifters in which it is possible to introduce a turns ratio which would enable the secondary voltage to be stepped up to the value required to allow the necessary distribution of turns. The penalty occurs in that the mains-fed section of the motor ($\frac{1}{3}$ of the whole for two phase-shifters or $\frac{1}{4}$ for four phase-shifters) would need to be fed through an additional static transformer.

In so far as it is possible to judge at this stage, we agree with Prof. Rawcliffe's preference for the phase-shift machine and with his reasons for that preference. We would go further and prophecy that, if a method could be devised to institute a correct entry-edge flux powered by the wasted exit-edge magnetic energy, there would be no doubt whatsoever of the commercial success of these devices, since they would then operate with full conventional machine efficiency and power output. Success in this direction is not, however, at present in sight. We find the constant-current approach much more informative for analytical purposes, though we recognize that where application is in question, constant-voltage results are essential and each of the papers includes sets of constant-voltage characteristics. The term 'conventional' as applied to the phase-shifters refers to their construction rather than their use. A large phase-shift motor at present under construction and a detailed analysis of pha shifter losses will be undertaken. Conventional machines have phase errors and there seems to be no objection to calling them such. With regard to Prof. Rawcliffe's last pa graph, certainly the most satisfactory practical result so far been the enthusiasm shown by the present generation of stude for electrical-machine research.

With reference to Mr. Holmes's comparison of the conventio and short-stator machines, the output of the latter is invers proportional to the speed only so long as the output is limi by rotor heating, i.e. to the right of the point on Fig. A wh the full and dotted lines join. If this be the case and a m efficient rotor cooling system is devised so that the rotor dissi tion is doubled, then the rectangular hyperbola shown in Fig will be raised so that each ordinate is doubled, and the out of the short-stator machine will approach that of the c ventional machine at 4000 r.p.m. We agree that, of the th machines mentioned by Mr. Holmes, the phase-mixer has best chance of meeting power/weight requirements.

We agree with Mr. Hill concerning the importance of econo factors, and regard as of great importance the fact that th developments have already fostered closer co-operation betw the industrial and academic sides.

Mr. Ball's suggestion of the hysteresis-motor application interesting, but we can foresee difficulties introduced by discontinuities in the stator magnetic circuit, although we h not, so far, put the suggestion to practical test. With regar planing machines, the speed of planers is not sufficiently f to enable a linear induction machine to be designed economic for this application.

Mr. Fong is correct in his comment on Section 5. There several ways of arranging the windings of phase-mixer mo so as to obtain the triangular (or other shapes) of block required. Space will permit only one example, which is sho in Fig. B. It will be observed that all coils have the sa
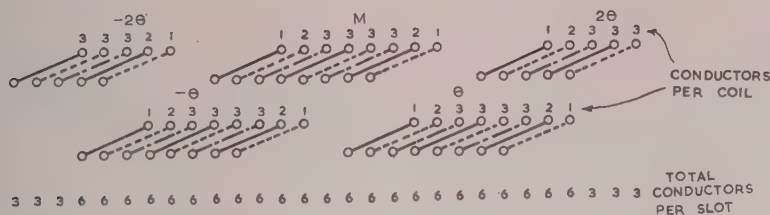
Fig. B.—Arrangement of windings for four phase-shifters.

———————— Red phase mains.
— — — — Yellow phase mains.
—●—●— Blue phase mains.
This notation applies to the phase-shift windings only when θ = 0.

h and that each slot contains the same total number of ns.

hese machines are more bulky than conventional machines he same speed and output, as Dr. Small suggests. Their ciency and power factor are likely to be lower. This is the e of continuously-variable speed. A similar price is paid in other types of variable-speed motor. A.C. commutator tors, Ward Leonard sets, etc., are generally between three four times as bulky. Even if our machines are still lower in ver/weight ratio, they may be worth while in some applica- s where a brushless machine is essential. The logmotor racteristics at different settings are similar to those of Fig. 10 the phase-mixer paper, except that the power levels are er at the lower speeds.

he concentrated losses in a flux-killing winding may not be serious as Mr. Clapham suggests. If the short-circuited ding is to be effective, its resistivity will be about ⅓ to ¼ t of the rotor. Since the coupling with the rotor winding will be good, the copper loss per unit area of stator in this region will be less than that of the rotor by about the same fraction. Nevertheless, it is true that the stator loss per unit area in the region of the short-circuiting grid can be considerably higher than that in the active zone, but this is compensated by the fact that the short-circuit winding can be an uninsulated cage.

The effects shown in Fig. 11 are less marked when the machine is on load. With regard to the use of more than one conductor per slot, this is only possible with Gramme-ring-type coils, which are generally uneconomical. Any other type of coil arrangement on motor stator or transformer secondary would fix a pole pitch which was contrary to the fundamental idea. The T-joints between interconnectors and rings are doubtless capable of being treated in the same way as those of modern well-designed rotors.

We agree with Mr. Clapham's comments on magnetizing current, power factor and competitive drives.

THE DEVELOPMENT OF RURAL ELECTRIFICATION

A Review of Progress.

By G. F. PEIRSON, Member.

(1) HISTORICAL SURVEY

Without the widespread use of h.v. and m.v. transmission and distribution lines, the supply of electricity to rural areas would not have been economically possible.

The snail-like pace of overhead-line development up to 1919 was accounted for by stringent regulations, and the serious recession in world trade which followed the 1914–18 War retarded the development of electricity for industrial purposes; but large-scale housing development proceeded in the built-up areas, and advantage was taken of this to publicize the many advantages of electricity in the home. Both municipal and private undertakings naturally built their power stations to deal with localized load, i.e. where industry was concentrated and the area heavily populated. Each undertaking could be regarded as a separate entity, mainly concerned with generation and distribution for its own particular locality, and many small towns were afforded a supply of electricity by non-statutory undertakings. Therefore there was no interconnected system for affording supplies to the wide areas populated by the rural community.

Following the 1919 Act some small co-operation between undertakings resulted from the setting-up of Joint Electricity Authorities. The effect of this Act, however, was relatively small, despite the evidence that the segregated use of power stations for isolated areas was costly and inefficient in both operation and the provision of capital assets.

The 1926 Act was passed to enable a national interconnecting Grid system to be constructed, so that the maximum use could be made of generation in the larger and more efficient generating stations, and bulk supplies could be given at other points which would permit inefficient generating stations to close down. It also enabled reinforcement to be given to other electricity supply undertakings' distribution networks without the need to construct further small generating stations. The Central Electricity Board became responsible for the construction of this 132 kV network and for the operation of all generating stations feeding it. At that time systems were operating on several different frequencies, and it was decided to standardize the frequency for the whole country at 50 c/s. This standardization of frequency and interconnection of generating stations were major factors in introducing concerted uniformity into the electricity supply industry of this country.

The sponsors of the Grid scheme deserve unstinted praise for creating a primary system which has enabled the development of electricity to proceed on a national basis. In 1926 it would have appeared illogical even loosely to connect the Grid scheme with rural development, since the principal object was the maximum use of power stations and the transmission of bulk supplies economically. As development of load has increased, however, it is obvious that the 132 kV transmission system has played a major part in providing reinforcements to the rural areas.

Owing to the world trade depression which began during war and persisted until the early 1930s, private undertakin found it extremely difficult to provide capital for any wholes development. Despite the adverse conditions, however, th was no dearth of pioneers, and a number of undertakings w powers to supply over wide areas commenced acquiring n statutory undertakings, and began to extend from the built areas with 66, 33 and 11 kV lines into the lesser-populated are

Towards the end of 1927 the Electricity Commissioners cal a representative conference on electricity supply in rural are with a view to co-ordinating the results of prior and concurre investigations and to obtaining such further information as w necessary for a general survey of the position. The report the conference[1] emphasized the fact that the provision of electrical service for rural areas of wide extent and low avera density of populations presented economic considerations of kind substantially different from those applying in urban are The moderate development of country town, village and fa electrification which had so far taken place covered only a sm proportion of the inhabitants; the full use of electricity in t farmhouse had yet to be realized, and the development of t farm process load waited on the advance of agricultural researc It was recognized that rural electrification entailed an init period of unremunerative working. This was a distinct deterre to development, and comparatively few undertakings we prepared to take the risks involved in capital expenditure for t purpose.

In May, 1929, the Minister of Agriculture announced that district in the area of supply of Bedford Corporation[2] had be selected in which to demonstrate the advantages of electric supply to typical rural communities and to test the dema This, the first scheme of its kind to be prepared by the El tricity Commissioners, was followed in 1930 by the Norwi Demonstration Scheme.[3] Two other schemes, which resembl these in some respects, were initiated in 1931 by the Dumfr County Council, and in 1932 by the Stewartry of Kirkudbrig A further scheme was undertaken in Shropshire by the W Midlands Joint Electricity Authority. These five schemes p vided valuable information about difficulties and potentialitie rural electrification. The need to construct most of the netwo at the outset, whereas consumers could only be connec gradually, meant that there was initially a very high cap expenditure per consumer. Hence in the early years the co of development were high and revenue was low, resulting deficits being incurred for a number of years by all five schem

The depression reached a climax in 1929 and Governm development grants in the form of loans at low interest ra were made to many electricity-supply undertakings as part national scheme for providing employment. This had the ef of enabling supply undertakings to extend their transmission distribution systems over much wider areas, and many n statutory undertakings were absorbed in the process. It also possible to provide many more consumers with a.c. sup

The Electricity Commissioners, in a 1930 study of the char due to the construction of the Grid, advocated that a com

nsive scheme should always be planned for the development of
 area as a whole, or in cases where very large rural areas
re concerned, for sections preferably of about 100 square
iles in extent. In various conferences with electricity under-
kings such comprehensive approach was strongly urged, as
re the needs for attractive tariffs, easy payment facilities for
ring, hire and hire-purchase for electrical appliances and for
od educational propaganda to encourage the regular use of
ctricity. Attention was drawn to the admirable pioneering
orts of a number of progressive undertakings.

The need for sufficiently large areas of development continued
 be urged, and at a further conference on electricity supply in
ral areas, convened by the Electricity Commissioners towards
e end of 1934, it was resolved:

That the development of electricity supply in rural districts is
impeded by the small size and large number of undertakings
operating in certain areas, and that the Electricity Commissioners
be asked to consider what steps could be taken with a view to
economic grouping of rural areas into appropriate units for the
efficient distribution of electricity by a smaller number of
undertakings.

It is hardly necessary to record that the terms of this resolution
ve been finally achieved. With the gradual recovery of world
de between the early 1930s and 1938, the impetus provided
 the Government development grants, the faith of the early
oneers and the whole-hearted co-operation of the Electricity
ommissioners, rapid progress was made in rural development.
The application of electricity to agricultural and horticultural
ocesses had proceeded slowly, and for a long time there was
sufficient information about the economics of farm operation
d the comparative costs of farm processes using different
rms of power and equipment. It was not until the Central
ectricity Board initiated a country-wide survey of rural and
rm electrification that the co-ordination of agricultural research
 a national basis was taken in hand. This survey was made
1935 and suggested the broad outline of experimental work to
 undertaken by the electricity supply industry in collaboration
th farmers, agricultural institutions and agricultural research
ntres. This plan of research was adopted by the British
ectrical and Allied Industries Research Association (E.R.A.)
d led to the establishment of its Section IV, Rural Electrifica-
n, which in subsequent years initiated numerous investigations
vering a wide range of agricultural and horticultural processes.
Between 1934 and 1939 rapid progress was made in rural
velopment, and an indication based on the mileage of low-
ltage mains erected in rural areas is interesting as a yardstick
 progress. In 1929 there were 3 700 miles of l.v. mains in the
ral areas of Great Britain; in 1939 there were more than
000 miles,[4] an increase of 440%. Apart from the l.v. mains
ich run from the transformer to consumers' premises, supply
thorities had to construct and maintain an even greater
leage of overhead lines, working at higher voltages, to supply
e transformers feeding the l.v. system.

To appreciate the significance of the figures quoted it must be
membered that in 1939 the populations of all the rural parishes
Great Britain represented a bare 20% of our total population,
t occupied 89% of the total area, giving an average distribution
 population of 115 per square mile, compared with 4 810 per
uare mile in urban areas. The fact that 67% of premises in
ral areas had a supply available to them by 1939 constitutes
notable achievement by any standards.

Following the declaration of war in 1939, electrical develop-
ents which were not directly related to the war effort virtually
ased, but in so far as farms were concerned, new connections
re still possible on the recommendation of the agricultural
mmittees which were set up. It was fortunate that such
cellent progress with the development of rural electrification

had been made prior to 1939, since the availability of electricity
supplies contributed in no small way to the national war effort.
Despite restrictions, the annual connections of farms during the
war years was of the order of 5 400, and this sustained progress
would not have been possible but for the 66, 33 and particularly
the 11 kV backbone systems which had been developed primarily
by supply undertakings prior to the war. Supplies of electricity
were also much more readily available in the rural areas for the
large service depots and ancillary depots required by the British
and Allied Armies. Furthermore, the manufacture of light and
heavy engineering equipment in locations remote from the
built-up industrial areas was practicable. The fact that progress
was made under such arduous conditions reflects the greatest
credit on all concerned.

The post-war years confronted the supply industry with added
difficulties in further development. Shortages and increased
costs of raw materials and of labour imposed physical handicaps
on the speedy development of rural extensions, particularly in
less-populated and more remote rural districts. At the same
time, conditions were beginning to improve in two important
respects. There was greater general prosperity in agriculture,
and the purchasing power of agricultural workers was being
raised by new standards of pay.

Rural housing depends on an electrical service for primary
domestic needs of lighting, heating and cooking; rural water
and drainage schemes, slate and stone quarries and craft indus-
tries require electric power. In modern agriculture electrical
energy is needed for numerous processes: in dairy farming for
milking, cooling, sterilizing, cleaning and washing; in poultry
farming for hatching, testing, rearing, food mixing, egg sorting,
and bird plucking; in arable and mixed farms for water pumping
and for driving barn machinery with a variety of operations,
such as cake breaking, corn grinding, root cutting, hop picking,
threshing and drying grass, grain and other products; in market
gardening for lighting, seed raising, soil warming and soil
sterilization. The variety of operations is great and derives
from the great diversity of Britain's farming countryside.

The essential difference between rural and urban distribution
systems is that the average number of consumers per mile of
line in the rural area may not be more than 10, whereas in
typical urban centres it may exceed 300. Hence there is in the
rural areas a much higher capital expenditure per consumer.
It was, however, apparent that the social and economic life of
the rural areas forms a pattern into which electricity enters a
common thread, providing modern amenities to village com-
munities and so helping to check the movement of population
to towns, accelerating the mechanization of agriculture, and
bringing power to rural industries.

Between 1945 and 1st April, 1948, the connection of farms,
farm-workers' cottages and rural housing were given some
priority, and an average of 6 500 farms were connected annually;
but more rapid progress was essential. During this period
many supply undertakings embarked on widespread publicity
campaigns and spared no efforts in their endeavours to educate
the rural community in general—and farmers in particular—on
the advantages of electricity supplies. Commercial staffs
included an officer who specialized in farming appliances, and
an efficient liaison was established with the Minister of Agri-
culture, the National Farmers' Union, agricultural colleges, and
other representative bodies. On the engineering side new types
of 11 kV line were designed and tested, and much research was
carried out with a view to minimizing the cost of rural develop-
ment. In all this field of activity the Electricity Commissioners
and the Electrical Research Association gave active support.

The next, and perhaps the most important, milestone in the
history of rural development was the passing of the Electricity

Act of 1947. The British Electricity Authority (later changed to the Central Electricity Authority) was established to generate electricity and provide supplies in bulk to the Area Electricity Boards, who were to be responsible for the distribution of electricity to their consumers.

The country was divided into Areas, and the power to supply was transferred from 560 private and municipal undertakings to 14 Area Boards. This had the immediate effect of erasing the boundaries which existed between the previous undertakings; the fullest use of existing systems became practicable, and future planning could be carried out on an area basis rather than a parochial one. On the engineering side, technical committees were set up under the Conference of Area Board Chief Engineers to consider all aspects of distribution engineering. The standardization of plant and equipment which has been achieved has led to economies permitting the greater use of available capital.

Under Section 1(B) of the Electricity Act, 1947, the electricity boards were directed to secure, so far as practicable, the extensions of supplies to rural areas. After Vesting Date—1st April, 1948—the Central Authority and the Area Boards considered the most equitable methods of implementing this duty, and decided to maintain and widen the scope of discussions with the Ministry of Agriculture, the National Farmers' Union, and the Country Landowners' Association, as well as other representative bodies. The Central Authority set up an agricultural electrical advisory section as part of their commercial department. The commercial departments of Area Boards intensified their campaign, and national overhead-line engineering panels were set up to study design and standardization.

At this point it is necessary to make some general comments on the position facing the Authority and the Area Boards at Vesting Date.

In considering rural development as a whole it must be appreciated that the pattern of the rural areas had undergone marked changes between 1938 and 1948. The rural towns and all the more populous villages already had supplies of electricity. The setting-up of industries adjacent to market towns had also converted sections of the rural areas into urban areas. Further development was therefore primarily confined to affording supplies of electricity to the smaller and remote villages and hamlets, and particularly to the many farms which still had no supply available. The capital cost per consumer was therefore an increasing factor, and with restrictions on capital governed by national economies, the position was extremely difficult.

It would not have been surprising if the total reorganization of the supply industry had initially adversely affected the progress of rural development, but actually record progress was made in the five years following Vesting Day. Between April, 1948, and March, 1953, the Area Boards connected about 49 000 farms to the public mains. The average was approximately 10 000 a year, compared with 4 000 in 1938, the last full pre-war year.

On the 19th June, 1953, the House of Commons passed a resolution urging that 'steps be taken to develop the supply of electricity in rural areas as much and as fast as possible'. In support of this resolution the Government announced that the electricity supply industry would be allowed to incur additional expenditure on rural electrification. No less important in its
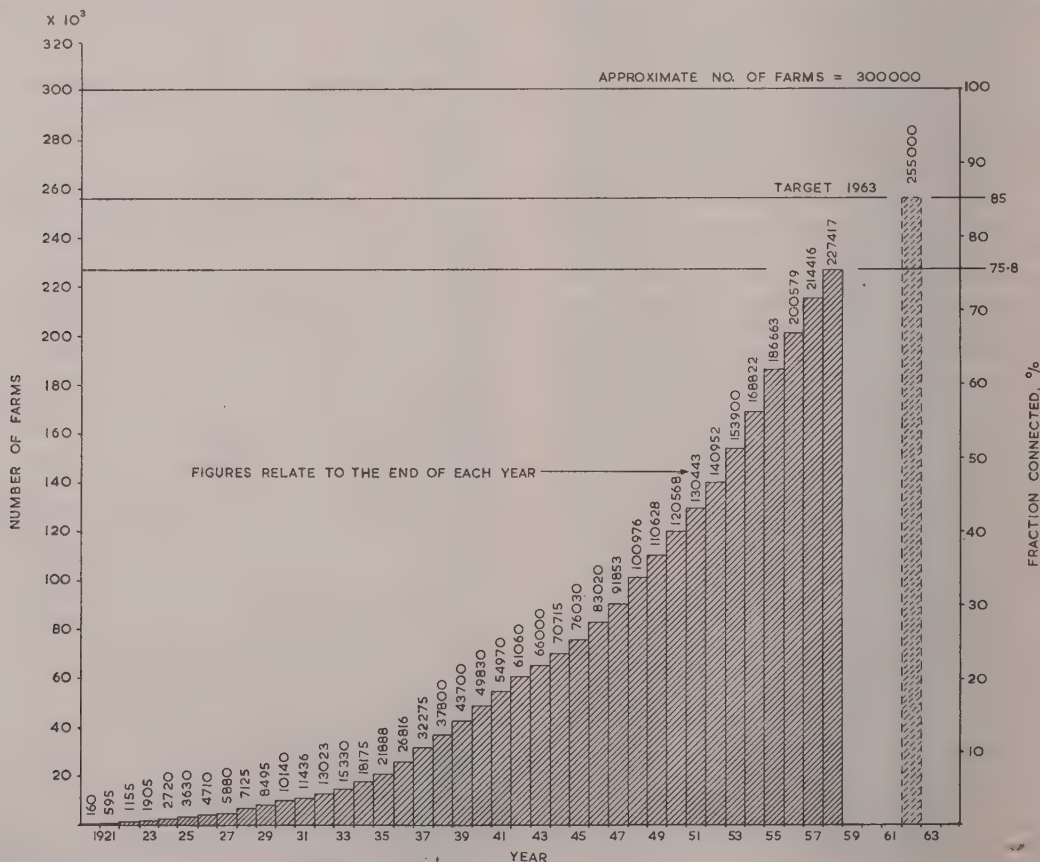
Fig. 1.—Progressive connections of farms in England, Wales and South Scotland.
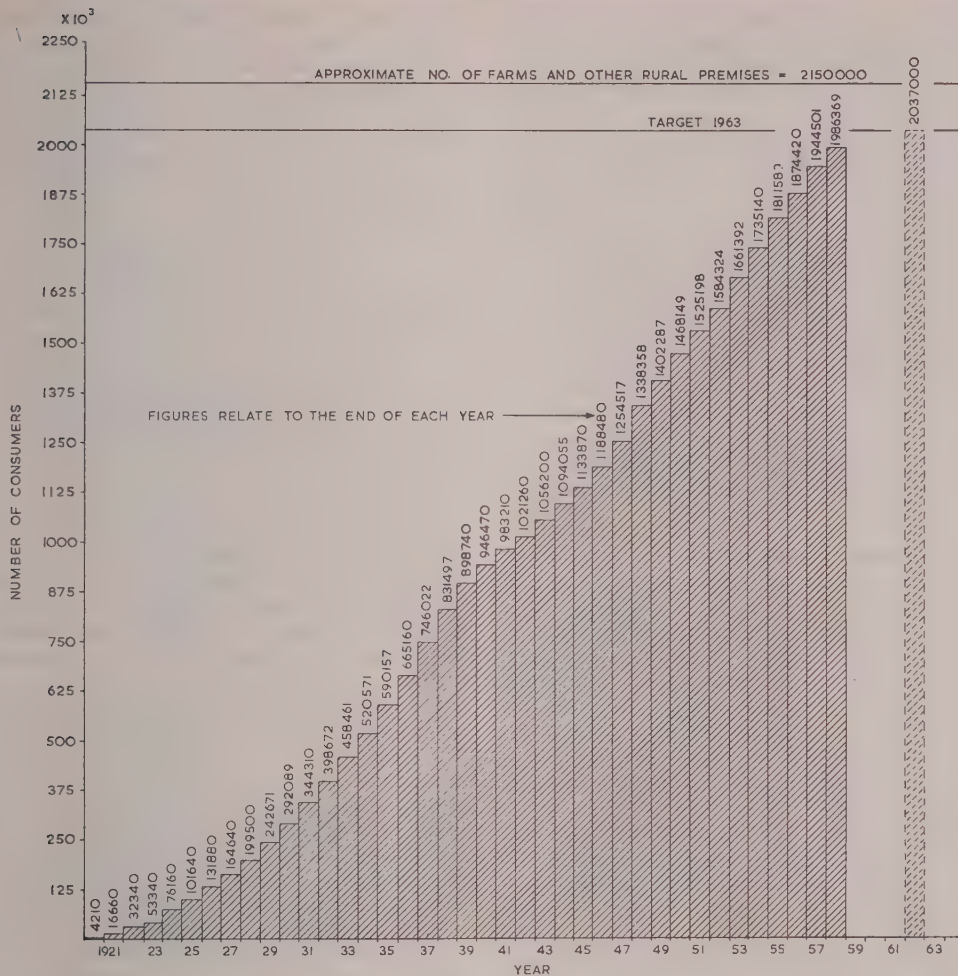
Fig. 2.—Progressive connections of farms and other rural consumers in England, Wales and South Scotland.

mplementary relationship was the removal of the ban pre-
ously imposed on promotional advertising.

These concessions enabled the supply industry for the first
ne to plan ahead, since experience had shown that a steady
anned programme was necessary for rapid progress at the
west cost. This is not possible without continuity of national
licy and promotional development.

In 1954 the British Electricity Authority and the Area Boards
epared a programme with the objective of connecting 85% of
farms by 1963. This involved the connection of a further
0 000 farms in two stages. During the first stage, covering a
year period to the 31st March, 1958, some 57 000 farms were
pected to be connected; and in the second stage it was hoped
give a further 43 000 farms a main supply. A target of this
der was regarded as practicable and satisfactory in the light
the proportion of remote and isolated farms posing special
oblems. Moreover, the aim of an 85% connection by 1963
as an average for the whole country, and it was realized that a
w Boards might take longer to reach it.

Under the Electricity Reorganization (Scotland) Act of 1954
e South of Scotland Electricity Board was established and
ok over the assets of the South East and South West Scotland
reas and of the British Electricity Authority in Scotland. To
ve a comprehensive record, the progress in the South of
otland Electricity Board is incorporated.
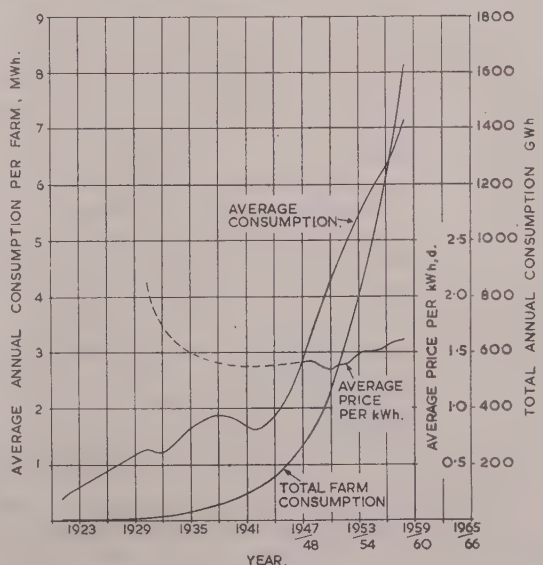
Fig. 3.—Progress of average and total farm consumptions and average
price per kilowatt-hour in England, Wales and South Scotland.

The very excellent results to the end of March, 1959, of this bold and ambitious programme are shown in Figs. 1–3, and the rate of progress is a tribute to everyone concerned.

The definition of a farm has always been loosely interpreted, but the figure of 300 000 quoted as 'total' includes 'those complying with the common definition of farm for tariff purposes, but excluding those without buildings or otherwise unlikely to require a supply of electricity'.

The work of the agricultural advisory service of the Area Boards, of the Electricity Council, and of such bodies as the British Electrical Development Association, the British Electrical and Allied Industries Research Association, the Ministry of Agriculture, Fisheries and Food, and the National Farmers' Union, has encouraged farmers and others in rural areas to make greater use of electricity supplies, but much more remains to be done in this aspect of electrical development. So far it has not been possible to secure an adequate financial return on rural electrification schemes, particularly in the early years, and if the capital resources of Area Boards are to be employed to the best advantage, a fuller use of electricity for farms is essential.

(2) CODES OF PRACTICE

Between 1892 and 1919 the responsibility for the preparation of regulations devolved upon the President of the Board of Trade, who had the assistance of an electrical adviser. No attempt has ever been made to produce a large detailed code, such as that, for example, of V.D.E. (Germany) or the United States of America's Safety Rules for the Installation and Maintenance of Electricity Supply and Communication Lines; however, regulations were included in the first Electric Lighting Orders passed by Parliament as required by Section 6 of the Electric Lighting Act of 1882.

The first British Safety Code was issued in 1896, and this was divided into two parts: (a) for securing the safety of the public, and (b) for ensuring a proper and sufficient supply of electrical energy, regulations as to aerial conductors being incorporated in part (a).

After the formation of the Electricity Commissioners, authorized under the Electricity Act of 1919, one of the first things they did was to create a precedent by asking The Institution of Electrical Engineers for its views on overhead-line regulations. The Institution set up a committee, and after considering its recommendations, the Commissioners published their first Overhead-Line Regulations, El.C.39, in 1924. This new code met with a mixed reception, and in 1925 there were requests from certain sections of the industry for modifications. Following a further consultation with both The Institution and the industry, a new Code, El.C.53, was published in 1928.

Throughout this period, careful consideration was given to the modification of regulations to make provision for the progressive development of overhead-line construction and design, and credit must be accorded to those responsible for appreciating that they were dealing with a rapidly developing industry.

A revision of El.C.53 containing certain minor modifications was published in 1931 as El.C.53 (Revised), and the next revision, dated 1947, included a new regulation recognizing lines constructed in accordance with B.S. 1320: 1946.

A proposed revision of El.C.53 (1947) prepared by the Code of Practice Committee was formulated, and this was presented as a paper on overhead-line regulations read by H. W. Grimmitt[5] before The Institution in 1949. In the meantime, however, the Electricity Act of 1947 had been passed, and the responsibilities of the Electricity Commissioners had been taken over by the Ministry of Fuel and Power (now the Ministry of Power). It was a natural sequence that the complete reorganization of the

supply industry, and the changed circumstances under which th Electricity Commissioners had previously operated, would dela the introduction of new overhead-line regulations.

Close liaison has continued between the Electricity Boards the Central Authority and the Minister of Power, through hi Chief Electrical Inspector, and it can confidently be anticipated that, as a result of experience and widespread investigations sinc Vesting Day, new overhead-line regulations will be forthcoming

(3) OVERHEAD-LINE DESIGN

(3.1) General

In the early 1920s, apart from the stringent regulations, th two main difficulties were the shortage of capital and the reluc tance of local authorities, landowners and farmers, and—no least—the Council for the Preservation of Rural England, t appreciate that, beyond city and urban boundaries, only th fullest use of overhead transmission and distribution lines woul allow progressive and economic development of electricit supplies in rural areas.

Overhead lines had to be designed to conform with the regula tions in force at the time, and it was extremely difficult to satisf the aesthetic tastes of laymen who were disinterested in economic and also convinced that overhead lines were an unnecessary evil The efforts of the early pioneers to overcome the strenuou opposition were rewarded by the marked progress made in rura electrification from the middle 1920s up to the outbreak of wa in 1939.

When the Electricity Commissioners were set up in 1919, a overhead line had to be designed to a transverse wind loading of 25 lb/ft² with a factor of safety of 10. It was obvious t the Commissioners that these stringent conditions require relaxing to cope with an expanding industry where cost woul be an important factor. The regulations were modified in 192 to require an overhead line to be designed to a transverse win load of 8 lb/ft² with $\frac{1}{2}$ in radial thickness of ice on the conductor with a factor of safety of 3·5 for wood poles and 2 for conductors

These conditions generally followed American practice, bu it soon became evident that these loadings were not completel satisfactory for the types of line erected in this country. A this stage the E.R.A. began a study of the problem, and in 192 a report on this aspect was published.[6]

Table 1 is extracted from this report, and it shows the win load on 30 ft poles with diameters of 7–12 in, the load bein assumed to act at a point 2 ft from the top of the pole.

Table 1

WIND LOADING ON 30 FT POLES OF VARIOUS DIAMETERS

Conditions	Wind loading at diameter of					
	7 in	8 in	9 in	10 in	11 in	12 in
	lb	lb	lb	lb	lb	lb
Calculated at 8 lb/ft² on projected area	55	61	68	77	86	95
Actual load at wind speed of 80 m.p.h.	20	27	36	49	64	84
Actual load at wind speed of 30–50 m.p.h.	20	17	15	14	11	12

It will be seen that the calculated load of 8 lb/ft² required the regulations is much in excess of the actual load due to wind of 80 m.p.h. and that at 30–50 m.p.h. is almost negligib The wind load on the pole is usually a very small percentage the total transverse load, particularly when small-diameter po

e used. When loading conditions were used for the standard ecifications, it was decided to ignore the load due to the wind a pole.

Towards the end of the 1920s it was appreciated that the evailing loading conditions of 8 lb/ft² wind and ½ in radial ickness of ice, with a safety factor of 2, were particularly nsatisfactory for copper conductors of 0·05 in² or less. In 29 the ½ in radial thickness of ice was reduced to ⅜ in. This itial loading was found to be unsatisfactory for 0·025 in² nductors; the tension on these in still air at 50° F is so little at they blow about in the breeze, requiring abnormal spacing prevent contact. More prevalent trouble was caused by vestock rubbing against poles, resulting in conductor clashing d so causing phase-to-phase faults. In 1937 the Commis- oners agreed to conductors up to 0·04 in² copper and copper uivalent of composite metal for use on h.v. lines to be strung ith an initial loading of ³⁄₁₆ in radial thickness of ice.

It is here necessary to interpose a little history to explain what ppears to be rather irrational progress. In the 1920s, most kV lines were erected with 0·1 in² copper conductors. This as the most economical line to erect, and also the electrical ad was such as to require these conductors, because their urpose was to connect small townships and the larger villages, e load at this stage not having developed to the extent to arrant the general use of 33 kV. As the networks increased, ur lines came into being chiefly to supply small villages, amlets and farms. It was essential to keep the cost of these ur lines to a minimum, and for this reason consideration was iven to smaller conductors and lighter poles. The ½ in ice ading was satisfactory when the minimum size of conductor as 0·075 in².

This piecemeal reduction of loading may appear irrational, but uring the period over which these reductions were made, a umber of light rural experimental lines were erected, and experi- nce of their reliability was obtained. In 1938 the E.R.A. were sked to prepare a specification for these light rural lines with a

view to submitting this proposal to the British Standards Institution so that a complete specification could be prepared. This was done, and the result is B.S. 1320: 1946. It was not only the work on wind loads which assisted in the preparation of this specification, but quite a lot of the work outlined in the 'Review of E.R.A. Work on Overhead Lines'.[7,8] Other important contributions were made by members of the sub-committee, whose combined experience was fully exploited, and the field work of enterprising undertakers, which will be referred to later.

The issue of B.S. 1320 permitted the use of unearthed steel-work, which was a radical departure from previous orthodox practice. The insulation of the pole itself is thus added to the normal insulator, and greatly increases the impulse strength to earth. It was required by the Overhead Line Regulations to earth the pole-top metalwork either at each pole or by a con-tinuous earth wire earthed at four places per mile. The reason for this was to avoid pole-top fires, and it was also assumed that the continuous earth wire erected below the conductors afforded some protection against lightning. It is extremely doubtful whether this arrangement did, in fact, provide any protection. It has been found from experience that unearthed lines give less trouble than earthed lines, and transient phase-to-earth faults due to birds and broken twigs settling on cross-arms have been eliminated.

Some engineers had grave fears that, with unearthed-line construction, pole-top fires or the danger of shock from a pole, would be enhanced should an insulator fail. An E.R.A. Report dispelled these fears.[9] A substantial number of wood-pole lines built prior to 1946 opeating at 11, 33 and 66 kV, have been unearthed, and many new unearthed lines in the same range of voltages have been built subsequently. It therefore appears that, following operating experience, unearthed wood-pole lines will be universally adopted.

Limited consent has already been given to the erection of unearthed high-voltage lines with conductors larger than 0·05 in²,
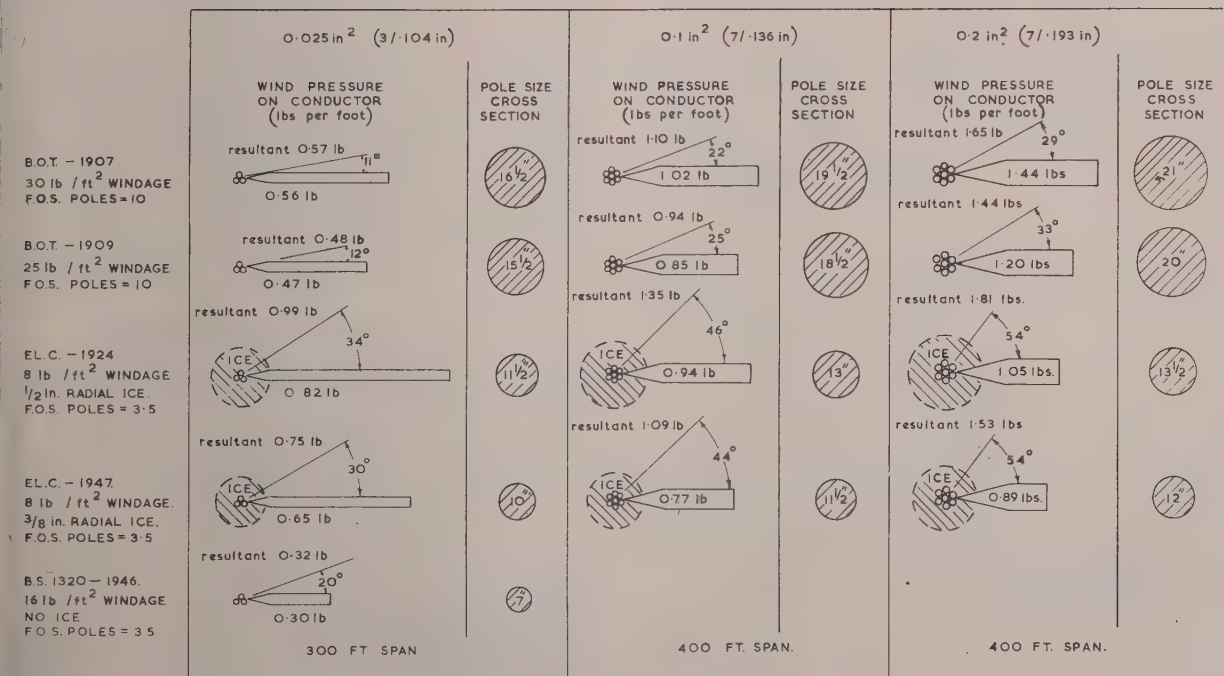
Fig. 4.—Physical effect of relaxation of overhead-line regulations on conductors and wood poles.

which are similar in appearance to the B.S. 1320 design, but comply with the loading conditions required by El.C.53 (1947 Revised). The physical effect of the relaxation of overhead-line regulations on conductors and wood poles is indicated in Fig. 4.

(3.2) Medium-Voltage Overhead-Line Design

The fundamental changes in medium-voltage overhead-line design are indicated in Fig. 5.

The 1920 and 1924 Regulations postulated that a guard beneath the phase wires supported by a split neutral was essential to safeguard the public from a conductor breaking and falling to the ground. The provision of this guard was unsightly and costly, and in practice broken conductors, although infrequent, were usually caused by physical interference rather than electrical faults.

The Regulations were relaxed in 1927 to permit the elimination of guards provided that the conductors were erected in vertical formation with a single neutral wire at the bottom position beneath the phase wires. This relaxation has led to the present-day standard design. Ornamental brackets, finials and pole roofs have been dispensed with, and a single-bolt fixing for insulators on line poles restricts the use of D-irons to heavy-angle, T, terminal and section poles. This arrangement has the merit of simplicity and economy, and has been generally adopted throughout the country since the issue of British Electricity Specification L.I. in 1951.

Fig. 5.—Design of m.v. overhead lines.
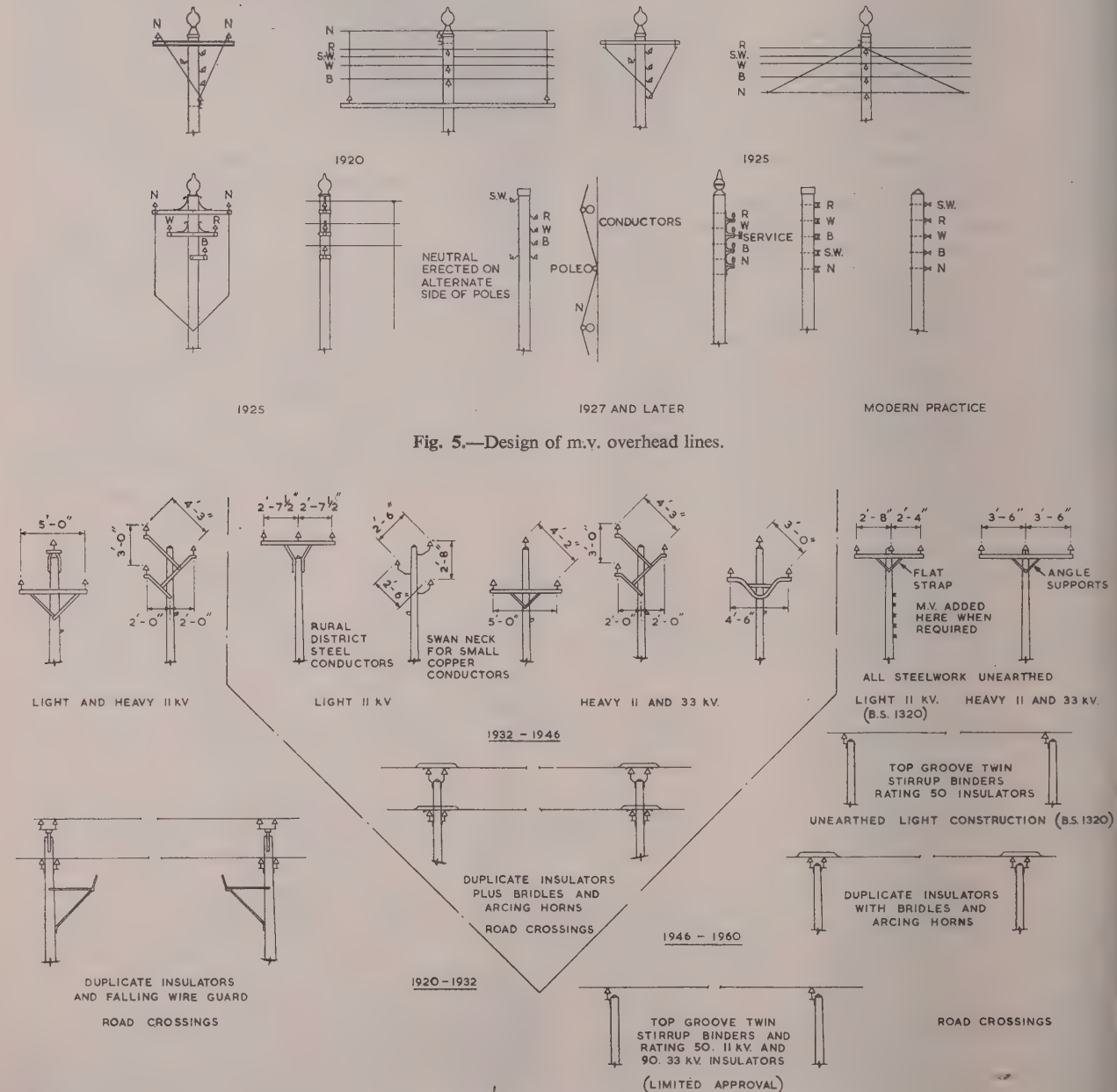
Fig. 6.—Design of 11 kV overhead lines.

(3.3) Overhead-Line Design

Space does not permit illustrations of the multifarious 11 kV designs tried out in the early pioneering days, but Fig. 6 illustrates the general trend of improved design which has resulted from practical experience in the field, and the close co-operation of the supply industry, the Electricity Commissioners and the E.R.A.

In 1931 the Electricity Commissioners gave consent for the erection of an 11 kV overhead line with conductors in horizontal formation, which was a departure from the orthodox triangular spacing. In this particular case, 7/·012 steel conductors were used instead of copper, the object being to reduce the costs for rural spur lines. It was appreciated that the carrying capacity of this type of line would be limited to about 200 kW, but the poles used were of the requisite diameter to carry larger-capacity conductors should replacement of the steel conductors ultimately become necessary through the growth of load. Many miles of this type of line were erected and commissioned, and although most of the steel conductors have now been replaced, several miles of the original conductors are still in service. Three-phase lines with conductors in horizontal formation proved to be extremely satisfactory in service, and the steel conductors used initially have given a useful life of at least twenty years.

At about the same time consent was given for a swan-neck-type 11 kV line employing No. 8 s.w.g. steel conductors on the basis of $\frac{3}{16}$ in ice loading. One large undertaking[10] adopted this swan-neck design as their standard for rural lines, but the handicap of having to design for $\frac{3}{8}$ in ice loading for 0·025 and 0·04 in² copper conductors still left the hazard of clashing conductors on these lines. Between 1935 and 1937 experimental swan-neck lines employing these conductors were built on the basis of $\frac{3}{16}$ in ice loading, and following the satisfactory performance of these lines in service, the Electricity Commissioners relaxed their requirements for the ice loading applicable to the smaller sizes of conductor.

In December, 1940, the Electricity Commissioners gave consent to the same undertaking to erect an unearthed line similar to B.S. 1320. This Consent permitted a 17ft statutory ground clearance and conductor tensions calculated on conditions which were subsequently published in B.S. 1320. The line was constructed in conjunction with the E.R.A. Committee which had been examining the possibility of a reduction in the cost of rural overhead lines. Approximately 100 lines of this type, varying from $\frac{1}{4}$ to 5 miles in length, were built and proved satisfactory in service before the Electricity Commissioners introduced relaxed regulations in 1942. These relaxations were included in El.C.53 (1947 Revise).

(3.4) Single-Phase Earth-Return 11 kV Lines

The latest development in 11 kV line design by the Electricity Boards, at present in the experimental stage, is the use of single-wire earth-return systems. This type of line is basically cheaper than the B.S. 1320 single-phase 11 kV line, and is suitable for connection to networks in which the neutral is solidly earthed, provided that the earth-return currents are not of sufficient magnitude to interfere with the normal system protective devices or Post Office communication systems.

The possibility of connecting earth-return lines to systems earthed through a resistance is being investigated, and the E.R.A. have designed a prototype high-speed relay with a view to overcoming present difficulties. This development work may result in future economies being achieved in the field of remote rural electrification where loads are likely to be comparatively small, and steel conductors will in most cases provide sufficient

carrying capacity and durability, and also enable long spans to reduce the number of line supports.

(3.5) 33 and 66 kV H-Type Wood-Pole Lines

No fundamental change in the design of 33 and 66 kV H-type wood-pole lines with conductors in horizontal formation has taken place, except for the introduction of unearthed steelwork, and a less liberal use of trussing tackle.

(4) OVERHEAD-LINE COMPONENTS
(4.1) Overhead-Line Supports

(4.1.1) Wood Poles.

Imported red-fir poles (*Pinus sylvestris*) have been used by the Post Office and supply undertakings for over 60 years, and experience has proved that a long life can be anticipated if they are properly seasoned before creosote impregnation. In this country, therefore, single and H-type wood poles are now used almost exclusively for 11, 33 and 66 kV overhead lines. A small number of 132 kV portal-type wood-pole lines have also been erected.

In the years immediately preceding the 1939–45 War the demand for wood poles was greatly accelerated by the development programme of rural electrification, and in the light of later experience it became evident that owing to a curtailed period for seasoning, many poles with a high water content had been impregnated, with the result that the creosote had not penetrated into the full depth of the sap wood. The result was that dry rot occurred after a few years of service, particularly just above and below ground level. During the war, supply undertakings were dependent on home-grown poles, mostly larch. There was no alternative, although it was appreciated that their life would be considerably less than that of the red-fir poles. A considerable number of poles erected during this period have had to be replaced, and to prevent further deterioration of poles affected to a lesser degree, an extensive programme of ground-line salts treatment has been carried out.

This experience does not detract from the versatility of wood-pole supports, and in an endeavour to avoid a recurrence of this trouble, Area Electricity Boards have stationed their inspectors at or within easy reach of pole suppliers' works, and all poles are now inspected and tested to see that they comply with the requirements of B.S. 1990, and that the creosoting is carried out in accordance with B.S. 913.

(4.1.2) Concrete Poles.

A limited number of overhead lines were built on concrete poles when imported wood poles were scarce, but owing to somewhat higher first cost and handling charges, there has been no marked tendency to adopt them for general use in this country. Another factor is that most of the new lines are erected with the steelwork unearthed.

(4.2) Insulators

The general design of insulators has not radically changed, except that for the last 20 years or so glass insulators have been available as an alternative to porcelain. Owing to its low first cost and an excellent service record, porcelain is usually the preferred material for pin insulators, while disc insulators in glass and porcelain are widely used on lines of all voltages.

For medium-voltage lines reel insulators have replaced the multi-shed type, and with the deep-groove type angles up to 25° can be negotiated without D-iron fittings.

For 11 kV service the present-day practice is the virtual standardization of 16 kV one-piece porcelain pin insulators, rating 50 to B.S. 137. This is one rating higher than that

permitted in B.S. 137 for 11 kV, but it provides an additional margin against breakdown and also complies with Overhead Line Regulations 1943 (relaxed), which permits single pin insulators, or alternatively single strings of disc insulators where a line crosses a public road. At strain positions, 10 in discs with ball-and-socket fittings, rating 50 per disc, to B.S. 137, have become the recognized standard.

For single-pole 33 kV lines, one- or two-piece porcelain insulators rating 90 to B.S. 137 have proved very satisfactory in service. At strainer positions, 10 in discs rating 50 with ball-and-socket fittings are used in strings of three.

For suspension insulators H-pole 33 and 66 kV lines, 10 in diameter discs rating 50 with ball-and-socket fittings are used, 3 or 4 in series for 33 kV and 5 or 6 in series for 66 kV.

Since the cost of glass-disc insulators is comparable with that of porcelain, they are now a popular alternative. From the technical aspect the glass insulator has the advantage that it requires no maintenance checking other than a visual inspection, since it does not chip, and if it is physically sound it is also sound electrically. On the other hand, in certain locations where malicious damage may be expected, glass is more vulnerable to stone-throwing.

For all ranges of voltage except medium voltage, the decision to use insulators with a rating one higher than the permissible minimum was partly dictated by the increasing use of arc-suppression coils on rural transmission and distribution lines.

Special conditions arise near the coast, owing to salt deposits, and in inland industrial areas, owing to pollution, where a longer leakage path is essential to minimize breakdown due to abnormal conditions. To meet these circumstances, special types of insulators with approximately $33\frac{1}{3}\%$ additional leakage path are available, and among these line-post insulators of original American design have proved to be very successful on 33 kV lines.

A degree of standardization of insulator pins and ball-and-socket couplings, as defined in B.S. 137, has greatly facilitated insulator changing in the field. Discussions are now taking place to standardize insulator fittings completely, with a view to providing a much greater degree of interchangeability.

(4.2.1) Television Interference.

A complex problem has arisen in respect of transmission- and distribution-line insulation with the widespread introduction of television.

With pin-type insulators capacitance currents flow from the conductor, stirrups or binder on an insulator to the insulator pin. Parts of the insulator will be in intimate contact with the live conductor and stirrups, while in other parts small air-gaps will exist which will offer large capacitance. As the voltage is increased from zero, these small air-gaps break down in rapid succession, giving rise to a series of current surges which cause television interference. Non-conducting greases have been tried without success, and although semiconducting (graphite) greases have proved successful, they are difficult to apply, since all air pockets between the insulator head and the live conductor and accessories must be eliminated. Alternatively, the insulator may be fitted with a metal cap or a stabilized or semiconducting glaze applied during manufacture. These glazes have been developed only in recent years, and some doubt exists as to the effective life of the semiconducting material. Investigations are proceeding to try and establish the cause of deterioration by electrolytic action on certain types of glaze in heavily polluted areas.

With disc-type insulators there are capacitance currents flowing down a string from the pin of one unit to the cap of the next; to do so they must break down the oxide dielectric which

is formed when little weight is available to keep the two metal surfaces in intimate contact. As before, the rapid succession of the breaking down of the dielectric causes current surges on frequencies in the television bands. At strainer positions, where the discs are under tension, no trouble is experienced, but at double suspension points, where one of the two strings is carrying little or no suspension weight, television interference has been experienced. In these cases some interference has been eliminated by the application of semiconducting grease on suspension strings, but the better method is the bonding of the pins and caps of adjacent units by short braid connections with the cap of the top insulator bonded to the cross-arm.

(4.3) Conductors

The high conductivity and durability of copper conductors has long been appreciated in the electrical industry, and apart from certain limitations on long-span construction, it is unlikely that any other conductor material would have received much consideration if it had not been for the all-important economic factor. Since 1949 the basic price of copper has risen rapidly and reached as much as £400 per ton. It therefore became necessary to consider alternative material for overhead-line conductors where previously copper had been used almost exclusively. Aluminium is the economic alternative to copper, and this has been used in three forms—plain aluminium for short-span m.v. lines, and steel-cored aluminium or aluminium-silicon-magnesium alloys without steel reinforcement for h.v. lines.

Experience with steel-cored aluminium on the 132 kV Grid lines has shown that this form of conductor has a long service life provided that it is not subjected to severe industrial atmospheric air pollution or salt deposits in coastal locations. Much of the trouble experienced has been corrosion of the steel core, and it is probable that this will be minimized considerably by the present-day manufacturing techniques, which provide for the application of a grease coating over the steel core prior to laying on the aluminium strands.

Apart from corrosion in certain areas, the principal difficulty has been to provide tension and non-tension joints which maintain satisfactory mechanical and conductivity qualities over a period of many years. Many of the joints put into service on s.c.a. conductors performed satisfactorily when first applied but deteriorated rapidly and resulted in many failures. Cold-flow compression joints have a good service record, and this type has been widely used to replace all other forms of joint on h.v. lines. A range of simple compression joints and connectors for use on m.v. and B.S. 1320 distribution lines using aluminium, aluminium alloy, or s.c.a. conductors has been developed to extend the compression-jointing principles to this class of distribution.

One Area Electricity Board was enabled to erect pilot schemes in 1951 as a result of the co-operation of manufacturers who produced suitable compression joints and compacting tools for use on m.v. and B.S. 1320 distribution lines using aluminium. These schemes were entirely satisfactory, and in view of high copper prices, standardization of plain aluminium for medium-voltage (except in industrial areas) and aluminium alloy for B.S. 1320 lines was adopted. Many hundreds of conductor-miles of both types have since been erected, and experience confirms that aluminium is a satisfactory alternative to copper.

Economically it has been found that for m.v. lines the saving in cost is the difference between the costs of copper and aluminium conductors: for light 11 kV lines using alloy conductors the saving is 90–95% of the difference in conductor costs, while the figure for heavy s.c.a. lines is 80–85%.

(4.4) Air-Break Switchgear and Isolator Design

Air-break switches and isolators were extensively used in rural systems, but suffered from the disadvantage that they had interrupting capacity, and flashovers when attempting to break transformer magnetizing and line-charging currents were common. Following the visit of the Electricity Supply Productivity Team to America in 1949, one Area Electricity Board imported from the United States a number of sets of 3-phase interrupter head switches which were rated as 600 amp at 5 kV. Tests on these were made at the high-power testing station of a switchgear manufacturer, and in addition to the Board's engineers, representatives of a number of British manufacturers who had expressed interest in these devices were also present. As a result, British manufacturers have developed interrupter heads for use on 11, 33 (Fig. 7) and 66 kV systems.

Fig. 7.—Interrupter heads fitted to bank of 33 kV air-break isolators.

With such a device fitted to an air-break switch the circuit is normally carried on the main contacts. When opening, however, the circuit is transferred to the interrupter head and is broken therein, the arc being drawn in a tube lined with fibre washers which emit an arc-extinguishing gas under the influence of the arc itself. The current is thus carried by the interrupter head only during the interrupting period. By the use of these devices, load currents up to 600 amp and magnetizing and charging currents up to 40 amp at 11 kV may be interrupted. This device does not replace circuit-breakers, but provides an increased flexibility of operation in rural systems without the danger of flashovers which occurred with the normal air-break switches and isolators.

(4.5) Construction—Mechanical Aids

Apart from design economies effected by Area Electricity Boards, much thought has been devoted to easier and speedier methods of construction. The first approach to mechanization was to use a power-operated auger for digging holes, and after searching here and abroad, a number of ex-U.S.-Army truck-mounted power-driven earth augers were obtained which also included a power hoist for erecting poles. These machines proved invaluable in speeding-up construction, and they also helped in many cases to solve acute labour-shortage problems. As an example, in normal soil, once the auger is in position it takes 3–4 min to complete the operation of excavating a 20 in-diameter hole to a depth of 5 or 6 ft (Figs. 8 and 9). Subsequent to the introduction of the American machines a number of British power-operated earth augers have been developed.

Fig. 8.—Post-hole borer excavating hole.

Fig. 9.—Post-hole borer being used to drop pole into bored hole.

Other developments to assist line construction have been the introduction of cross-country all-wheel-drive trucks and Land Rovers, the latter being helpful for a wide variety of field work, such as delivering poles to sites and pulling out conductors.

Other items, including lightweight cranked-axle pole pick-ups which enable two men to load and handle poles weighing 12 cwt, have proved their worth in the final field-delivery stage, especially when a Land Rover is available to play the role of tractor. Aluminium alloy, which has been used in the construction of these pick-ups, has also been used for the production of light-weight pole-lifting pikes and other items of tool equipment.

(5) PROTECTIVE DEVICES FOR RURAL ELECTRIFICATION

Protective devices for rural systems should be capable of reliably detecting and clearing faults due to climatic conditions, birds, cattle rubbing, etc., which occur on overhead lines. Many of these faults produce currents of low magnitude, owing to the small conductor sizes, long line lengths and—more often than not—poor earthing conditions. Since the protective device is generally installed on the line itself, with consequent exposure to all weather conditions, the duty imposed thereon is for the most part very arduous.

(5.1) Fusegear

The protection of h.v. overhead lines by fuses is one of the oldest methods employed. Early types consisted of a plain fuse wire in an insulating tube, and were mainly designed to the melting requirements. Later designs, however, had a more positive approach to the circuit-breaking function of the fuse, and today fuses having a breaking capacity of 150 MVA at 11 kV are available. H.V. fuses at present employed may be of the expulsion, liquid or powder-filled types, in many cases the fuse itself acting as the circuit-isolating feature. The two former types are generally suitable for the fault-power levels encountered in rural systems, but where the level is high the powder-filled fuse is employed.

The liquid fuse, which employs a spring to separate the fuse element in blowing and to inject insulating liquid into the arc path, has widespread use, but sometimes gives trouble due to the breaking of the glass tube and leakage of the liquid. The expulsion type is cheaper in first cost and maintenance, and with recent research making possible high breaking capacities, its application is increasing. The powder-filled fuse, which has an inherent high speed of operation combined with a current-limiting characteristic, is normally employed only where faults of the order of 250 MVA are encountered.

The unit system of protection being desirable, early installations tended to employ h.v. fuses at each transformer, but while operations from transformer failures were infrequent, surges due to lightning storms often resulted in widespread fuse blowing without permanent damage to apparatus. This led to the concept of fusing transformers in groups, usually at the point where a spur line is tapped on to the main line, and it is this method which is generally used today. Overload protection for the transformer is provided by fuses on the l.v. side of individual units, and the use of h.r.c. powder-filled fuses for this purpose combined with the comparatively high rating of the group fuse, provides adequate discrimination between h.v. and l.v. protection.

Approximately 80% of the faults occurring on rural systems are due to transient causes, resulting in the operation of the protective devices without permanent damage to the system. It will therefore be appreciated that the quality of the supply will be improved if the circuit can be quickly resumed by the restoration of the protection, and to achieve this the repeater fuse was introduced. In this design the action of isolating a spent fuse is arranged to operate a change-over contact to bring another fuse into circuit, thus restoring the supply, Units having up to three replacement fuses, with or without a time-lag

device, are obtainable. The operation of the repeater fuse is, however, somewhat unreliable under icing conditions. The repeater fuse cannot discriminate between transient and persistent faults, and in the latter case reserve fuses are expended to no useful purpose.

(5.2) Reclosers

Pole-mounted circuit-breakers are available, and for reasons given above are arranged to provide automatic reclosing facilities. The energy for this is provided by a falling weight attached to a chain passing round a pulley, the number of reclosures provided varying between three and six. For the smaller numbers of reclosures, circuit-breakers having a rating of up to 100 MVA are available, but this capacity normally decreases as the number of reclosures is increased. Open-circuit times of the order of 30 sec are normally employed in order to ensure that apparatus such as motors are automatically disconnected from the system before the supply is restored. Protection against earth fault may be provided by the use of current transformers mounted on the terminal bushings, and a sustained-fault lock-out feature may be fitted to prevent further reclosures if tripping recurs within a predetermined time of reclosure.

(5.3) Arc-Suppression Coils

On rural systems, where earth faults predominate, a method of providing protection is by the use of arc-suppression coils. These take the form of a reactor connection between the neutral point of the system and earth, the impedance of the reactor being such that when an earth fault occurs the capacitance current supplied to the fault by the two sound phases is neutralized by the inductive current in the coil. The resultant current in the fault is therefore theoretically zero. Since the coil is tuned to the system capacitance, tappings are required to cater for varying operating conditions.

Since the earth-fault current on an arc-suppression-coil system is only that due to inaccuracies of tuning, the fault condition may be allowed to persist for a time sufficient to enable switching operations to be carried out and the faulty feeder isolated without interruption of supplies, indication of the faulty feeder being obtained by the use of sensitive wattmeter-type relays. The voltage to earth on the sound phases is, however, raised to full line voltage under fault conditions, and if it is not desirable that this condition shall persist, arrangements may be made automatically to short-circuit the coil by a neutral resistor, after a predetermined time, thus permitting the operation of the normal earth-fault protection to isolate the line.

Arc-suppression coils give protection against transient earth faults and prevent such faults developing into those of a more persistent nature. The increase in the line-to-earth voltage, however, demands that line insulation shall be at all times in good condition, otherwise cross-country faults occur. These are, in effect, phase-to-phase faults against which the arc-suppression coil is no protection. The loss of a feeder or feeders from any cause results in mistuning of the coil and the remainder of the system, which may have serious consequences under conditions such as lightning storms. The placing of numerous small coils at different points in the system does, however, help in this direction. The arc-suppression coil is not an expensive item of apparatus, and since it provides protection for a complete network, may be economically justified for earth-fault protection of rural systems.

(5.4) High-Speed Automatic Circuit Reclosers

Both the repeater fuses and reclosing circuit-breakers previously mentioned suffer from the disadvantage of limitation to the number of operations available before a visit to site is

quired in order to ensure that the device is fully reset and a
ll operating cycle is available. The high-speed automatic
cuit recloser which overcomes this disadvantage originated in
merica, and its introduction into this country by the Area
ectricity Boards was the subject of a paper by Peirson, Pollard
d Care.[12]

The high-speed automatic circuit recloser minimizes damage
apparatus and prevents unnecessary blowing of associated
ses by virtue of a high tripping speed on the occurrence of a
ult. If the fault is of the transient type, it may clear during
e short open-circuit time interval of 1 sec before subsequent
closure. This rapid tripping also reduces the possibility of a
ansient fault developing into a persistent one. If, however,
e initial fault is of a persistent nature, isolation of the faulty
ction of the network is obtained by the blowing of an associated
se on a delayed tripping operation following this closure.
lternative operating cycles are now available giving combina-
ons of tripping operations varying from four instantaneous to
ur delayed, and breaking capacities of up to 75 MVA may be
otained.

The type of recloser in general use in this country today is
sentially a series solenoid device which utilizes the fault energy
open the circuit-breaker contacts and at the same time to
narge the spring for subsequent reclosing. This requirement
ntails some dependence of the maximum fault capacity of the
nit on its normal tripping current, and for the lower ratings
nposes some limitations. This recloser is manufactured in

Fig. 10.—Set of three single-phase high-speed automatic circuit
reclosers on 11 kV 3-phase line.

ngle-phase units (Fig. 10) with inter-phase coupling, and is
ranged to provide tripping and reclosing on the faulted phase
ly, but for locking open and on manual operation, all three
nases are operated simultaneously.

Another design which has recently been introduced, having
all three phases in one tank arranged for 3-phase tripping and
reclosure, derives the energy for charging the reclosing spring
from a solenoid connected across the incoming terminals through
auxiliary switches which ensure that the coil is in circuit only for
the time taken to recharge the spring. Full breaking capacity is
available throughout the range of trip-coil ratings, and provision
is made for the inclusion of an earth-fault trip coil operated
from current transformers mounted in the terminal bushings.
It is possible to mount this type of recloser on a single line pole.

The operational experiences of an Area Electricity Board's
11 kV system partly protected by arc-suppression coils, and
another Board's 11 kV system partly protected by high-speed
auto-reclosers are compared in Table 2; both systems have
approximately 6 000 miles of 11 kV overhead lines.

Table 2

COMPARISON OF FAULT-PROTECTION EFFICACY

Area	Type of protection	Line length	Number of supply interruptions per 100 miles per annum
		miles	
A	Arc-suppression coil	4 173	28·8
A	Solid earth and fuses	2 269	47·3
B	High-speed recloser	2 017	3·58
B	Solid earth and fuses	3 947	49·7

A momentary interruption by a recloser which successfully restores supply is not
regarded as an interruption.

On balance of performance the high-speed auto-recloser pro-
tection shows to advantage, although it is more costly to provide.
However, it must be remembered that more and more important
loads are developing in the rural areas, and continuity of supply
is of prime importance.

(5.5) Earthing

Much valuable research into the methods of earthing has
been carried out by supply undertakings and the E.R.A., and
these comments are confined to general progress. In industrial
and urban areas good earthing facilities have generally been
available for supply undertakings and consumers in the form of
metallic water mains and underground cable systems. The
tendency for the earthing of consumers' installations now shows
a marked leaning to the fullest use of underground cable sheaths,
owing to the increasing use of non-metallic pipes for both new
and existing water systems, rendering them no longer reliable
for earth continuity.

In rural areas, particularly in regions where neither water nor
underground cable systems exist, the obtaining of low-resistance
earths has presented a major problem at both distribution sub-
stations and at consumers' premises. The general principle
during the early years of rural electrification was for supply
undertakings to depend on a buried earth-plate for the neutral
at distribution substations and for wiring contractors to provide
an earth point at consumers' premises. The varying and high
resistivity of the mass of earth in rural areas made it almost
impracticable to provide earths of sufficiently low resistance to
ensure the safe operation of apparatus under fault conditions.
The enterprise of manufacturers at this stage in producing
simple forms of earth testers enabled a more unified approach
to be made to earth resistances, and supply undertakings buried
copper radiating from the earth plate to reduce the resistance of
the neutral point. This method was partially successful, but
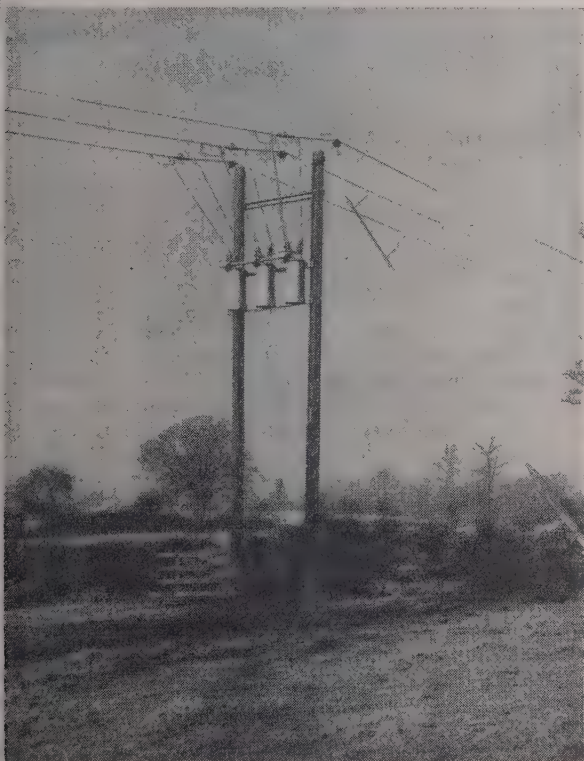proved very costly.

The next stage was the introduction of voltage-operated earth-leakage trips which were used primarily on consumers' power circuits. Apart from other considerations, the question of cost was of primary importance, and consumers were reluctant to meet additional wiring costs, even in the interests of personal safety. No criticism could be offered on the voltage-operated earth-leakage device, but it is necessary to test this device and the earth connection periodically, since failure to function under fault conditions defeats the object for which it is intended.

Another form of added protection for the consumer is the provision of a continuous earth-wire on m.v. overhead lines, but this is not favoured, owing to its high initial cost and the dangerous conditions which would result from breakage. These developments, aimed at the safe operation of electrical appliances, fell short of the desired standard, particularly from an economic point of view.

In the meantime, on the Continent, in America and in the Commonwealth, protective multiple earthing had been used extensively. The original Special Regulations and Approval to Protective Multiple Earthing was produced by the Electricity Commissioners, with the concurrence of the Postmaster General, in 1940. The conditions laid down were somewhat onerous, and in 1949 an Area Electricity Board which had taken an active part with the Electrical Research Association in preparing recommendations for the relaxation of p.m.e. regulations, applied to the Ministry of Fuel and Power for permission to apply them to two extensions in the rural area south east of Macclesfield. Permission was granted, and in August, 1950, an extension was granted by the Ministry to cover the whole of the rural territory of this Electricity Board.[13] Other Electricity Boards have subsequently received consent from the Ministry to apply p.m.e. throughout their rural areas.

Experience indicates that, with the present Regulations, i.e. those which now appear as Appendix F of the 13th Edition of The Institution's Regulations for the Electrical Equipment of Buildings, protective multiple earthing is satisfactory and the most economical. The possibility of a broken neutral has not been entirely eliminated, so that some small modifications may be found necessary in the light of more widespread experience. However, the negligible incidence of accidents and damage to consumers' apparatus to date leaves little doubt as to the efficacy of this form of earthing.

The introduction of unearthed steelwork on h.v. transmission and distribution lines has greatly simplified earthing problems, and at major substations the general practice is to fit earthing resistors to limit the magnitude of earth-fault currents of h.v. systems.

(6) RURAL TRANSFORMER DESIGNS

Over the years there has been little change in the fundamental design of transformers, but developments have resulted in improved techniques in manufacturing process and the application of new materials. These include a great increase in the use of cold-rolled grain-oriented steel as the core material, which permits higher flux densities and reduced iron losses. The introduction of this material in continuous strip form allows cores to be wound instead of laminated, and uncut cores of this type have been manufactured for 3-phase units up to 100 kVA.

Improved forms of insulation and research into the behaviour of transformer windings under surge conditions have resulted in transformers having high impulse strengths—a feature particularly valuable for rural distribution transformers exposed to lightning conditions.

In 1950, following co-operation between representatives of transformer manufacturers and Area Board chief engineers, a national specification for distribution transformers, both pole- and ground-mounted, has resulted in economies advantageous to manufacturer and purchaser alike.

The diverse nature of the rural-system load curve, and the demands for economic development of such systems, led to the introduction of a variation of the smaller sizes of standard pole-mounting distribution transformer specifically designed for this purpose. Such units have a very low iron loss and are capable of overload capacities of up to 100% for periods of up to two hours following continuous operation on full load.

At major distribution substations the use of large units incorporating the new techniques and fitted with automatic on-load tap-changing equipment permits a high quality of supply to be given to rural consumers.

(7) CONTINUITY OF SUPPLY

(7.1) Live-Line Operation

In addition to the introduction of the more modern forms of protection, such as arc-suppression coils and high-speed automatic reclosers, methods have also been introduced to reduce the number of pre-arranged interruptions for the purpose of making new connections. The arrangement of outages for this purpose becomes progressively more difficult, owing to many continuous processes in manufacturing and certain aspects of agricultural operations which are dependent on a continuous supply of electricity, while in the home, apart from domestic appliances, many complaints arise from the loss of television programmes, particularly those covering national and international events.

It was known that in America engineers carried out 'hot line' maintenance work on all types of line, irrespective of voltage. In Britain the approach has been made on the basis of actual connection or disconnection being carried out from ground level, which in effect means that the work is performed under the same conditions as those which apply when dealing with rod-operated pole-mounted fuses.[14]

The initial difficulty was to control insulated operating rods of the length required for making connections to conductors which may be 25–30 ft above ground level. This control problem was solved by the introduction of a guide stick (Fig. 11) which, when hooked over the conductor to which a connection is to be made, functions in exactly the same way as a cue rest when using a billiard cue. The solution was simple but effective. Operating rods up to 28 ft long are manufactured in either hollow-spar, silver spruce or glass-fibre tubing, but the latter is favoured because its electrical properties are stable under wet or dry conditions, and the weight is 8 lb compared with 10 lb for other types (Fig. 12).

This method of live-line connection can be used on almost any horizontal or triangular conductor formation of 11 kV line provided that an underrunning earth wire is not present. Innumerable pre-arranged interruptions have been avoided since the introduction of live-line connections, and the organization of maintenance has also been made much easier on lines equipped with such facilities. Live-line working has made, and will continue to make, an important contribution to the supply engineer's ideal—continuity of supply.

(7.2) V.H.F. Radiocommunication

The advent of v.h.f. radio, which has superseded the universal dependence on the Post Office telephone for communications, has greatly accelerated communication systems.[15] During maintenance and emergency operations, direct contact can be
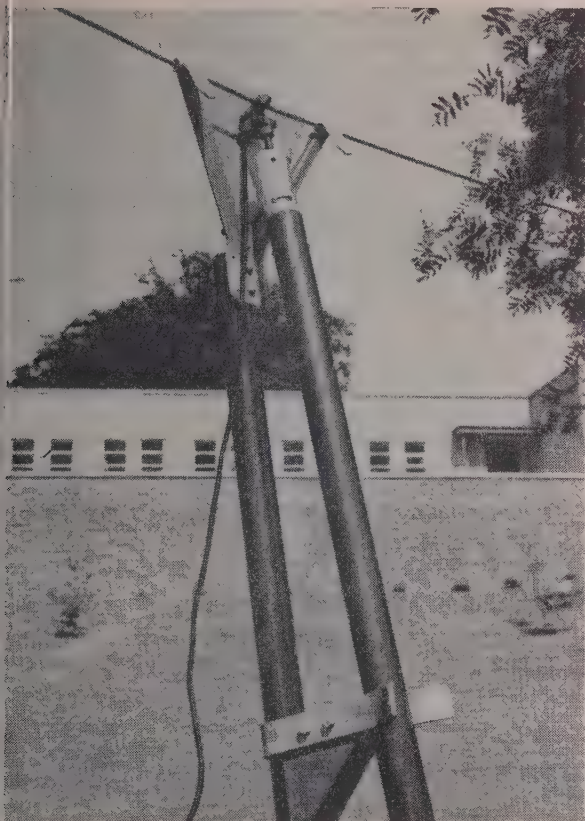
Fig. 11.—Live-line tools.
Guide stick in position and clamp being tightened on to line with operating rod.

Fig. 12.—Live-line team making a T-tapping off an 11 kV line.

aintained between system control stations and field engineers, d point-to-point contact is available between field engineers d their respective gangs. On the domestic side, service vans n be put in direct contact with their service centres and can instructed to deal with complaints without returning to epots for verbal instructions. These facilities are a great boon the rural areas, where Post Office facilities are often remote om the cross-country routes of overhead lines, and the time-ving factor is incalculable.

(8) DESIGN OF RURAL DISTRIBUTION SYSTEMS

Between 1920 and 1930 much progressive pioneering work was rried out by supply undertakings to extend supplies of elec-icity to rural areas. With limited capital it was possible only extend 6·6 and 11 kV systems beyond the limits of urban eas, and the small return on what capital was available pre-nted a definite financial risk. The general principle governing ese extensions was to route the h.v. overhead lines to embrace e market towns and the more prosperous villages en route. was at this stage impracticable to allocate sufficient capital provide ring-main feeds to afford alternative supplies, and stems were erected in 'tree formation'. As loads increased, terconnecting lines were erected between the larger load centres provide better standby facilities and also to form new back-ne lines for additional development.

Three-phase medium-voltage systems with a centrally located stribution substation were generally accepted for distribution villages and adjacent farms. Where 11 kV lines were routed ross farm properties, a limited number of single-phase supplies

was afforded to the more progressive farmers, who were far-sighted enough to appreciate the many advantages of a supply of electricity.

Since the initial demands of villages and farms were low, it was necessary for economic reasons to keep transformer sizes down to the minimum required to deal with the immediate plan plus a modest allowance for future development. The usual range was 15, 25, 50, and 100 kVA 3-phase and 5–10 kVA single-phase for farms afforded isolated supplies. In the light of later experience the installation of the smaller sizes of 3-phase trans-former proved to be false economy, since it was found imprac-ticable to balance loads over three phases with the limited capacity available.

Serious consideration was given at this stage to a wider use of single-phase distribution, particularly for farms, farm groups, and the smaller villages and hamlets. This method was favoured by many of the supply undertakings empowered to supply large rural areas. There is no doubt that the scales in favour of single-phase distribution were finally turned by the success of the Dumfries County Council scheme,[16] which proved the practicability of single-phase distribution so long as there was a good 3-phase 11 kV backbone within reasonable reach of the single-phase 11 kV ribs. Another innovation was the intro-duction of 3-wire single-phase m.v. distribution lines which provided a 460/230-volt supply. Where the disposition of consumers was favourable, this method had certain economic advantages over the 3-phase 4-wire system, although it meant the introduction of 460-volt single-phase motors, which was not universally favoured. Single-phase distribution with trans-formers at the focal point of load has subsequently been

exploited to the full in rural areas, with resultant large economies.

Between 1930 and 1940, owing to the growth of load, the capacity of the 6·6 and 11 kV network in rural areas proved inadequate, and supply undertakings found it necessary to carry out major reinforcements to maintain voltage regulation. Generally, the provision of 33 kV overhead lines to supply major substations was found to be the most economical, but a few undertakings favoured 66 kV transmission. At these two voltages a very extensive transmission network had been built up throughout the rural areas of this country by 1940. Since the war, much more major reinforcement has been carried out in rural areas, at 33, 66 and 132 kV, and this will undoubtedly continue as the demands for electricity increase.

The method of reinforcement has been governed by the initial layouts of 33 and 66 kV transmission systems by the original private undertakings, so it is not proposed to deal with the merits of varying methods, but a great measure of saving has been achieved by the Electricity Boards in reducing the number of 33 and 66 kV circuit-breakers without endangering flexibility of operation.

It can be stated that, in so far as h.v. transmission and distribution lines are concerned, the costs have been contained at an economic level. This has been achieved by simplification and standardization of designs, and advantage has been taken of the relaxation of the overhead-line regulations over the years, which, in addition to reducing costs, has also improved the reliability of overhead systems.

The availability of electricity supplies in the rural areas is a measure of the devotion and enterprise of which the industry can be justly proud.

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A SURVEY OF STREET LIGHTING AND ITS FUTURE

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SUMMARY

The accepted principles of street lighting are reviewed in conjunction with the requirements of the British Standard Code of Practice for Street Lighting. British and oversea techniques and standards are compared, and some important recent experimental work and installations are described. These factors are used to assess the desirable trend of street lighting in the future.

(1) INTRODUCTION

The purpose of street lighting is to improve the safety and amenity of roads at night. For main roads the emphasis is on safety and for side streets or residential roads the emphasis is on amenity.

The funds available for street lighting compared with most other forms of lighting are extremely limited, particularly in the United Kingdom, so that every device for making the best use of the available money must be exploited to the full. The cost of a modern main-road installation including amortization, power and maintenance is about 1d. per square foot per annum. No other comparable lighting amenity is expected to proceed on such a meagre budget.

To a considerable extent British practice has been based on a type of road surface, common 20 years ago, which assumed a high polish as a result of traffic wear. Rough, dark surfaces having better skid-resisting properties) are now common, and these aggravate the technical difficulties of lighting the road. In addition, the demand for better street lighting is increasing both from lighting engineers and the general public.

The situation is reviewed in the following sequence: Present practice is examined in the light of the British Standard Code of Practice for Street Lighting; Continental and American practice are compared with British practice; and some recent research on the problem is summarized. From this review some conclusions are drawn on the desirable trend of street lighting in this country for the next few years.

(2) PRINCIPLES OF STREET LIGHTING

(2.1) Silhouette Vision

It is now well established that the best visibility on the road will be produced if the road surface and surround can be made bright while objects on the road are kept relatively dark.[1,2] The silhouette vision which results becomes increasingly effective as the brightness contrast between the object and its background is raised. Below a certain threshold contrast the object will disappear against its background.

This silhouette vision in a lighted street is not as far removed as one might expect from the type of vision enjoyed in daylight. Objects on a road by day are commonly seen to be darker than their background, although the brightness levels are now so high that modelling and colour also play an important part in the mechanism of seeing.

(2.2) Creating the Bright Road Surface

Each lantern in an installation generally produces a bright patch on the road surface with the now well-known characteristic T-shape. The 'head' of the T appears to extend across the road nearly opposite the lantern while the 'tail' extends towards the observer. This peculiar shape will be produced by a uniform light source giving the same intensity in all directions and is a characteristic of the road-surface reflection properties and the perspective geometry involved (see Fig. 1). If the road is smooth and well polished the 'tail' will be long and bright and the 'head' of the patch will be relatively small and less bright (Fig. 1, dotted contours). On a rough road the 'head' will tend to predominate, the 'tail' being shorter and of lower brightness. On a very matt surface the 'tail' may disappear completely leaving the 'head' forming a bright band across the road near the post (Fig. 1, full contours).
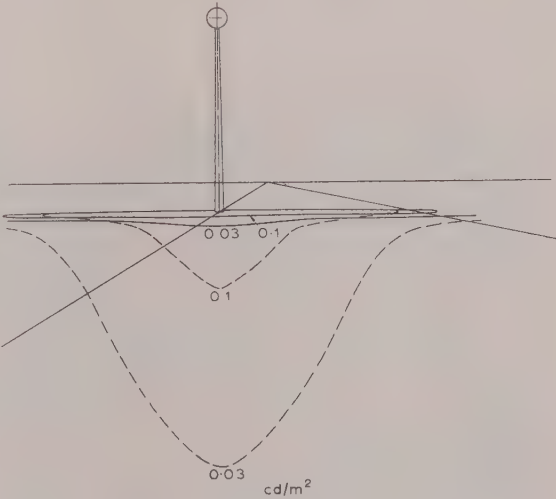
Fig. 1.—Bright patch from uniform source of 1 000 cd.

- - - - Iso-luminance contours for smooth surface.
———— Iso-luminance contours for rough surface.

In practice, roads vary considerably in surface texture and colour, so that no standard condition can be assumed by the lighting engineer; however, the modern trend is definitely to lay rougher roads for their anti-skid properties.

The bright patch appears to extend very little, if at all, beyond the foot of the post, even when, as is usual, the illumination distribution on the road is the same beyond the post as in front of it. Clearly, there is no direct or simple relationship between the brightness distribution and illumination distribution on the road surface.

The shape of the patch can be controlled to some extent by the light distribution from the lantern. Light at high angles, i.e. near the horizontal, is necessary to produce the 'tail', but no amount of light at these angles will produce a useful 'tail' if the road surface is unco-operative. On the other hand, the 'tail' produced on a smooth road surface can be removed by cutting off the light at these high angles.

A complete installation is built up of lanterns so arranged that their bright patches marry together; an observer moving along the road will see continuously before him a bright surface against which objects are silhouetted. The road surface is not necessarily the whole of the background against which objects will be seen. In urban areas the pavements, fences, building faces, etc., may all form part of the background, particularly on bends, and it is important that these should also be made adequately bright.

(3) BRITISH STREET LIGHTING

(3.1) Main Road Lighting.   Group A

(3.1.1) Types of Lighting.

The British Standard Code of Practice for Street Lighting[3] recognizes two principal types of lighting, the first being divided into two sub-types:

    (a) Non cut-off lighting.
        (i) High-angle beam.
        (ii) Medium-angle beam.
    (b) Cut-off lighting.

The descriptions refer to the intensity distribution given by the lanterns in a vertical plane parallel to the axis of the roadway (Fig. 2).

The light emitted at high angles in the street direction determines (subject to the road surface) the length of the 'tail' to the T-shaped patch; it also causes glare. Hence, to reduce glare, the high-angle light must be reduced. This is achieved largely by lowering the peak angle (the angle of maximum intensity relative to the downward vertical). The lanterns must now be spaced more closely together or the road surface will be lighted in patches. The three types of street lighting represent successive stages in the process of lowering the peak angle. The main differences are summarized in Table 1.
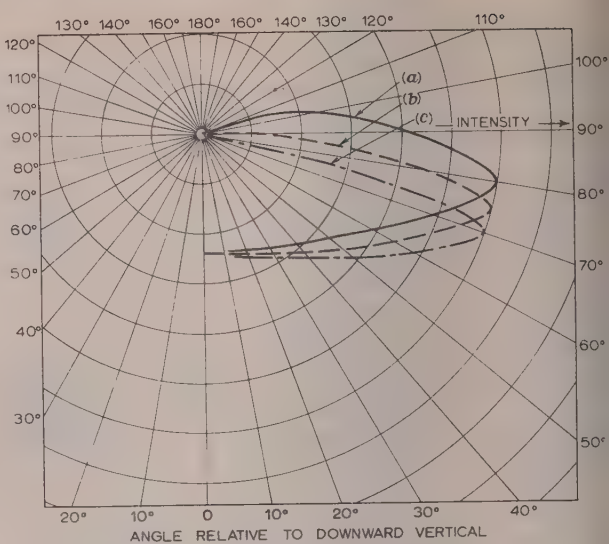
Fig. 2.—Typical light distributions.
(a) High-angle beam.
(b) Medium-angle beam.
(c) Cut-off.

beams are sometimes 'toed-in' about 5° towards the roadway producing a 'non-axial' distribution.

(3.1.2) Choice of Lighting to be Used.

The choice of the type of lighting to be used in a normal installation turns on a number of factors, aesthetic, technical and personal, some beyond the control of the lighting engineer. The most important are as follows:

    (i) Amount of light to be provided.
    (ii) Glare.
    (iii) Patchiness.
    (iv) Ratio of spacing to mounting height.
    (v) Colour.
    (vi) Appearance of installation (lanterns and columns, etc.).
    (vii) Cost.

These factors are for the most part closely linked. For

Table 1

MAIN CHARACTERISTICS OF THREE TYPES OF STREET LIGHTING

	High-angle [Fig. 2(a)]	Medium-angle [Fig. 2(b)]	Cut-off [Fig. 2(c)]	Refer also to Section
Peak angle	80°	75°	70°	
Light above peak ..	33% of total output may be emitted above horizontal. No limit	Less than half maximum intensity above 86°	Negligible above 80°	
Patch size	Long tail	Short tail	No tail	3.1.2.3
Glare	Maximum	Reduced	Negligible	3.1.2.2
Spacing	120 ft average, staggered	120 ft average, staggered or in line	90–100 ft average, in line	3.1.2.4
Cost	Cheapest	Middle-price	Dearest	

The standard mounting height for all systems in Great Britain is 25 ft plus 5 ft minus 1½ ft.

The conical light distribution, i.e. the light distribution around the lantern at a fixed angle to the downward vertical and containing the direction of maximum intensity, is not considered to be very critical. For normal main-road lighting an asymmetric conical distribution is generally used with two main beams directed substantially up and down the road. These

example, the cost of an installation will depend on the spacing and amount of light required, and a preference for a particular colour may influence the cost, appearance and glare in an installation. However, it is convenient to consider the various factors in turn.

(3.1.2.1) Amount of Light to be Provided.

The amount of light recommended for a main-road installa

is 2 600–7 000 lumens (below the horizontal) per 100 linear [feet] of road. Most modern traffic-route installations give [bet]ween 4 500 and 6 500 lumens per 100 linear feet.

[3].2.2) *Glare.*

[E]ven in a high-angle-beam installation the glare will not be [suff]icient to impair visibility significantly, provided that the road [sur]face is fairly well polished; it will generally, however, be [un]comfortable. The amount of discomfort sensation experi[enc]ed varies widely with different observers. The Code makes [a n]umber of recommendations aimed at mitigating the effect of [gla]re; and, in particular, it states that the ratio of maximum [inte]nsity to the average intensity below the horizontal (the [dir]ectional intensity ratio) should not exceed 6 and should [pre]ferably not exceed 5.

[T]he colour of the light also affects glare to some extent, so [tha]t, for example, a mercury installation will appear to a majority [of] observers to be more glaring than a similar sodium installa[tio]n. This is dealt with in more detail in Section 6.1.

[3].2.3) *Patchiness.*

[A] principal objective in main-road lighting is to produce a [uni]formly bright road surface from the driver's viewpoint so [tha]t objects on the road which appear in silhouette against the [bri]ght background are conspicuous in any position. Uniformity [of] brightness is, however, an ideal which is never achieved in [pra]ctice and some patchiness must be accepted. So far it has [pro]ved impossible to state in photometric terms what type of [lum]inance distribution on the road will produce a patchiness [wh]ich is just acceptable to the road user; indeed it has not even [pro]ved possible to define 'acceptable' patchiness. The recom[me]ndations in the Code ensure an acceptable uniformity in all [bu]t the most difficult cases. Three factors, in particular, deter[min]e the patchiness of an installation. They are:

(i) The type of road surface.
(ii) The light distribution from the lanterns (see Section 3.1.1).
(iii) The spacing/height ratio (see Section 3.1.2.4).

[T]he colour and, more particularly, the texture of the road [sur]face play a very important part in the patchiness of an [ins]tallation. For example, a dark rough surface may shorten [the] 'tails' of individual bright patches to such an extent that the [pat]chiness of the installation becomes unacceptable. However, [in] wet weather, the rough surface may break up the surface film [of] water, thus avoiding the long bright streaks often seen on the [oth]er smooth surfaces.

[3].2.4) *Spacing/Height Ratio.*

[T]he mounting height for main-road lanterns is normally 25 ft. [For] high- or medium-angle beam lighting on a straight road a [sta]ggered layout (lanterns on alternate sides of the road) with [a s]pacing of 120 ft is recommended, i.e. a spacing/height ratio [of] 5. The fact that the same spacing is recommended for the [tw]o types of light distribution means that greater patchiness [mu]st be accepted in medium-angle-beam installations. It is [un]wise to approach the maximum permissible spacing for these [lat]ter installations if it can possibly be avoided. For cut-off [lig]hting the lanterns must be mounted in a single row preferably [ov]er the centre of the road with a spacing of 90–100 ft, i.e. [a s]pacing/height ratio of 4. On bends the spacing must be [re]duced, except with cut-off lighting, and the lanterns should [be] mounted on the outside of the bend.

[3].2.5) *Colour.*

[T]he most economical lighting is usually obtained from lamps [wi]th poor colour and bad colour-rendering properties, since they

are efficient and can be accommodated in relatively small lanterns. Hence the majority of main-road installations use either high-pressure mercury-vapour (h.p.m.v.) or sodium lamps. For the most acceptable colour, either tubular fluorescent or tungsten lamps are used. Fluorescent lighting has become increasingly popular for the lighting of important thoroughfares and shopping areas. The running costs are competitive with other forms of lighting, but the initial cost of the large lanterns needed to house the lamps is greater and their appearance by day has not been without criticism. Tungsten lamps are now little used for main-road lighting because of their low efficiency and consequent high power consumption.

More recently the so-called mercury/fluorescent lamps have appeared on the market. These give quite good colour and are reasonably compact. Their popularity has increased rapidly in the past two or three years, but their cost is still rather high and they have not yet been fully exploited.

It is important to remember that, at the low brightness of a street-lighting installation, colour is of little importance to a driver. To pedestrians, particularly in well-lit shopping areas, it is more significant.

(3.1.2.6) *Appearance of Installation.*

The appearance of an installation by day is a matter on which opinions are bound to differ, and it is outside the scope of the paper to discuss in detail the aesthetics of street-lighting installations. However, it is generally agreed that a large number of closely spaced columns, particularly on dual carriageways, gives an unsightly appearance of a 'forest of poles'. In the particular case of the dual carriageway the problem can often be resolved by using cut-off lanterns mounted in a single row on the central reservation.

Another solution is to light each carriageway separately with lanterns facing the oncoming traffic (Fig. 3). This does not

Fig. 3.—'Uniway' installation on a dual carriageway.

alter the daytime appearance, but it halves the sources visible by night and reduces, materially, the total power required.

The large lanterns required for tubular fluorescent lamps are often an eyesore. However, with care it is usually possible to avoid the worst pitfalls of design particularly for those places where the appearance of the streets is of national interest and cost is not the primary consideration.

(3.1.2.7) *Cost.*

It is evident, from the above considerations, that the purchaser of a main-road lighting installation must decide how much he is

prepared to pay for the following features and to what extent he can compromise between them:

(a) Quantity of light.
(b) Freedom from glare.
(c) Freedom from patchiness.
(d) Good colour.
(e) Good appearance.

For example, if one is susceptible to glare one must accept a medium-angle beam installation with perhaps some patchiness or a cut-off installation at closer spacing and consequent increase in cost. If cost is the primary consideration a high-angle-beam installation will invariably be used with the largest permissible spacing. Such an installation will produce glare.

The cost of operating an installation (including amortization) varies considerably with local conditions. Broadly, however, the three main discharge sources—sodium, colour-modified h.p.m.v. and tubular fluorescent—are about equally expensive. If one insists on tungsten for its good colour one must pay some 50% more.

Cut-off lighting will cost some 20% more than non cut-off if the mounting height is unaltered but the columns are spaced more closely. If the column height is raised the spacing need not be altered and the cost will rise by perhaps less than 10%.

(3.2) Side-Street Lighting. Group B

The lighting of roads other than traffic routes is dealt with in Part II of the Code. These roads differ widely, but two broad categories are recognized. Group B_1 lighting is appropriate for streets in heavily-built-up urban areas where front gardens and forecourts are small and there are no trees. Group B_2 lighting is appropriate for roads in suburban residential areas which are often tree-lined and have wide footpaths or verges and deep front gardens. For both types of lighting the mounting height is 15 ft and the spacing should not exceed 120 ft, normally in staggered layout.

For Group B_1 roads the lighting is designed broadly on the same basis as Group A (main road) lighting, although the amount of light and the power of the lamps is much less. A non-axial asymmetric distribution is normally used with a vertical light distribution of the high- or medium-angle beam type, the latter being preferred to avoid glare. Cut-off lighting is not normally used. For Group B_2 roads, a more nearly symmetrical light distribution is recommended, since the footpaths, verges and front gardens form a large part of the area to be lit.

The amount of light to be provided in a side-street installation is based on the total luminous flux emitted from the lanterns and should be between 600 and 2 500 lumens per 100 linear feet of road. To achieve comparable results Group B_2 lighting normally requires more flux than Group B_1.

The quantity of light available in a side-street installation is not usually sufficient to meet all the requirements, and, in particular, it is not usually intended to be sufficient to enable the motorist to proceed without his headlamps. Indeed the marked difference in luminous flux between a side-street and main-road installation, together with the low mounting height, is intended to indicate clearly to the motorist that he is driving in a Group B locality, and the onus is on him to use his headlamps if necessary. For this reason the temptation to introduce an intermediate standard between Groups A and B lighting has so far been resisted.

The colour of the light in a side-street installation is more important than in main-road lighting because of pedestrian traffic, and tungsten lamps have been widely used in spite of their low efficiency. The introduction of the mercury/fluorescent lamp may eventually change this position, but the initial cost is higher and the colour, though good, is not yet completely satis-

factory. The bluish-white appearance of the source tends give a cold impression, particularly at low levels of illumination. Plain mercury and sodium lamps are often used where a relative high level of lighting is preferred to a good colour.

Recent experiments in side streets suggest that the non-axi asymmetric light distribution commonly used is not the mo suitable except possibly for minor traffic roads, where, fo economic and other reasons, full Group A lighting is no appropriate. These experiments are discussed in Section 6.2.

(3.3) Summary

British street-lighting practice is based on the assumption tha if the layout of the installation, the type of light distribution an the amount of light are within certain broadly defined limits, th result as to road brightness, patchiness, glare, visibility, etc., wi be satisfactory. Spacing/height ratios of 5 : 1 for non-cut-o lanterns (staggered arrangement) and of 4 : 1 for cut-off lanter (in-line arrangement) are commonly used.

The type of lighting chosen in any situation will turn o questions of local preference, aesthetics and particular economics.

The existing British Code on which present-day practice based was evolved at a time when street surfaces were con siderably more polished than those now coming into use. Th effect of the change is so significant that the whole matter o light distribution and layout needs to be reconsidered.

(4) STREET LIGHTING ABROAD

On the Continent and in North America the approach t street lighting, as formulated in their Codes of Practice or simila documents, is basically different from that in Great Britai With one or two exceptions they specify the average horizont illumination which must be achieved on the road surface togeth with uniformity ratios which are intended to keep the illumina tion diversity within certain limits. It is true that street lightin abroad often presents a different problem from that in th country. For example, the wide straight road is common America and on the Continent, whereas it is the exception in th country. Nevertheless it is a point of considerable interest th these basically different approaches should continue to exis particularly since we abandoned an 'illumination' concept ov 20 years ago and have not regretted it.

The Dutch recommendations on public lighting specify th average luminance (photometric brightness). A close control set on the permitted variation in luminance across the road, b rather less emphasis is placed on uniformity along the roa length; the resulting installation tends to be patchy to British eye

In principle, this approach to the problem is good, but th relationship between road luminance and road illumination so complex that it is difficult to predict the road luminance fro the installation data, and it is even more difficult to design installation to give a prescribed luminance distribution. It therefore necessary to fall back on rules of thumb based experience. Thus the Dutch recommendations state that, f the type of light distributions commonly used, an averag illumination of 10–15 lumens/m^2 will produce an averag luminance of 1 cd/m^2* and an acceptable uniformity w normally be achieved with a spacing/height ratio of perha $3\frac{1}{2}$: 1. The emphasis, in practice, is shifted from road lumi nance to road illumination.

In the American Standard Practice for Street and Highw Lighting various types of light distributions and installation la outs for different road situations are broadly specified. No cut-off or semi-cut-off lanterns with spacing/height ratios

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* A luminance of 1 cd/m^2 is the photometric brightness of a surface producing intensity of 1 cd/m^2 of projected area in the direction of measurement.

l or 5 : 1 are usual. The level of lighting is specified in
ns of the average illumination on the roadway; and the
rsity of illumination, expressed as the ratio average/minimum
nination, must not exceed 4 : 1. Great importance is
ched to a high coefficient of utilization,* which is a natural
ollary to the concept of roadway illumination. It is interest-
to note, however, that the fluorescent-lamp lantern is an
mitted success in spite of its inherently low coefficient of
lization, and there are indications that American lighting
ineers are having second thoughts about their method of
cification. As one American[4] recently put it, 'higher-angle
t-candles are worth more in pavement (road) brightness than
-angle foot-candles'—a fact which has been recognized and
ed upon in Britain for the last 20 years or more (though in
ns of the intensity distribution rather than illumination
ribution).

(5) COMPARISON OF BRITISH AND FOREIGN TECHNIQUES

n spite of national differences in methods of specification
re is clearly much in common since, to a considerable extent,
y all reduce in practice to some control of the light distribu-
n from each lantern (including its light output) and of the
cing and mounting height. The illumination concept
bably only persists because it can be relatively easily under-
od and measured. But since the illumination contains no
ormation on direction of incident light it would seem logical
refer only to the intensity distribution from the lanterns. It
nteresting to note that, if the lanterns are mounted at twice
ir original height, the average illumination on the road will
nearly halved, but the average road luminance will not
essarily be reduced by this amount; indeed the luminance of
ne parts of the road may well be increased.
Probably the most important difference between British and
eign practice, however, is in the attitudes towards glare and
tchiness. Glare, to the Continental, is something to be
ided at almost any cost, while in Britain a fair amount of
re is considered to be normal. Continental installations
signed to produce the minimum of glare use cut-off lanterns
th low beam angles and the results are usually patchy by our
ndards, in spite of the fact that their spacing/height ratios
e more favourable than ours. In this country, where economic
nsiderations have compelled us to use less favourable
cing/height ratios and where uniformity of road brightness
considered to be a prerequisite to good street lighting, some
re must be tolerated.
If the Continentals are over-sensitive to glare it is certain that
in this country are over-tolerant, and it seems likely that
ring the next few years we shall move closer together over the
mpromise between glare and patchiness.

(6) SOME RECENT EXPERIMENTS

In the last decade a good deal of experimental work has been
dertaken which not only indicates the need for improving
eet lighting but also offers guidance on how the various
oblems may be solved.

(6.1) Main-Road Lighting

The principal requirement of main-road lighting is safety for
e road user, and in recent years the Road Research Laboratory
s made extensive investigations into the effect of street lighting
road accidents.[5] It is now beyond reasonable doubt that a
ange from poor street lighting to Group A lighting reduces
ght accidents by about 30%. This appears to be accompanied

* Percentage of bare lamp light falling on roadway.

by a slight increase in the speed of the traffic so that the benefit
is twofold. It has been further argued[6] that, since a personal
injury accident at night costs about £700 and since one mile
of street lighting costs about £700 per annum, a saving of one
such accident per mile per annum would pay for the lighting.
The case has not been proved, but there is a widely held view,
supported by many lighting authorities, that a new Group A
installation can be installed and maintained at no cost to the
community as a whole.

Further experiments by the Road Research Laboratory[5] show
that road-reflection properties deteriorate as the skid resistance
improves, and, since skid resistance is of paramount importance,
it seems unlikely that the present trend towards rough dark
surfaces will be reversed. Attempts to produce artificial aggre-
gates suitable for both their skid resistance and lighting properties
have failed on the score of economy and durability. Road
engineers are now laying materials so rough and dark that the
road-surface brightness has been reduced to one-half or less
(Fig. 4). As a result, installations of the type which were satis-
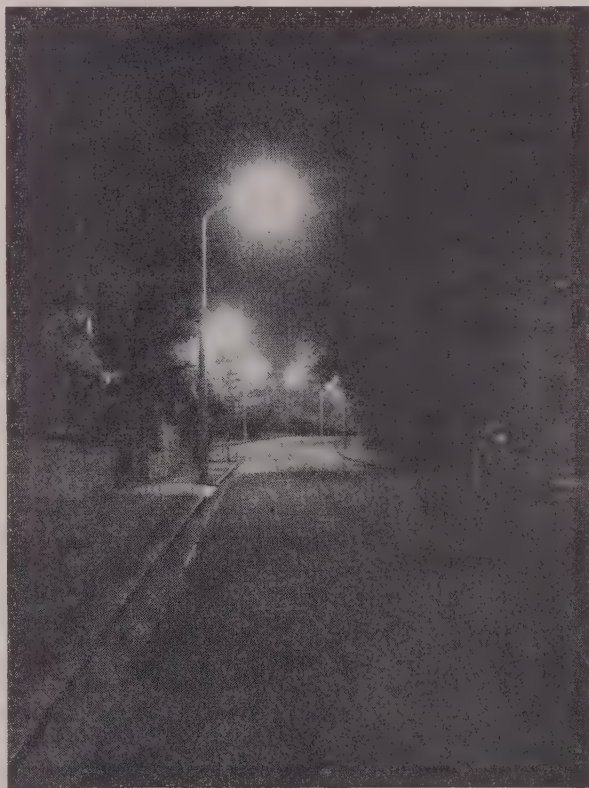
Fig. 4.—Comparison of rough and smooth road surface.

factory with the older road surfaces are now patchy and the
road brightness is so low that glare has increased sometimes to
an unacceptable level. Consequently street lighting in this
country has tended to deteriorate in the last few years. This
trend will continue unless our lighting systems are designed to
satisfy these new and difficult surfaces.

It is evident from observation and experiment that some light
sources are inherently more glaring than others. For example,
in a formal street-lighting test made in this country to compare
plain mercury and sodium installations,[7] similar in all respects
except colour, it was found that 80% of observers found the
mercury installation more glaring than the sodium. Interest-

ingly, this marked bias against the glare from the mercury installation was not accompanied by a significant preference for the sodium installation, so that it would appear that other factors are tending to offset the deleterious effect of glare. Nevertheless the indications are that special attention should be paid to the intensities emitted at high angles from mercury lanterns; these intensities should be reduced as far as possible, particularly if they are unlikely to make a useful contribution to the road brightness.

Some interesting experiments have also been made in Holland to compare street lighting using sodium and colour-corrected mercury lamps.[8] Here the installations are mainly of the cut-off type, so that direct comparisons with British non-cut-off installations should not be made.

The results may be summarized as follows:

(a) The average road luminance for colour-corrected mercury lighting needs to be 1·7 times that for sodium lighting to appear equally satisfactory.

(b) The uniformity of road brightness appears to improve as the average luminance is increased. Observers are satisfied with a poorer uniformity of luminance from sodium lighting than from colour-corrected mercury lighting.

(c) Eighteen sodium installations appraised for glare fell in the category 'satisfactory to unnoticeable', while of ten mercury installations so appraised only three fell in this category and the remaining seven fell in the category 'just acceptable to satisfactory'.

(d) In a static visibility test it was found that to achieve a given visibility distance under mercury lighting required a road luminance 1·8 times that for sodium lighting.

These results are perhaps more dramatic than those which have been published so far in this country, but it should be remembered that Continental cut-off lighting is very different from the type of lighting we are accustomed to in this country. In addition, on the Continent they are very sensitive to glare and relatively insensitive to patchiness.

Nevertheless, there is now a considerable weight of evidence to suggest that, other things being equal, a sodium installation will, apart from its colour, stand up to a critical visual appraisal rather better than a mercury installation, particularly perhaps when the sources are visible.

(6.2) Side-Street Lighting

Most side streets which have been lit during the past quarter of a century use lanterns giving a non-axial asymmetric light distribution similar to that given by main-road lanterns. In fact, side-street lighting has been based on main-road practice. This type of lighting is not necessarily the most suitable, particularly in residential roads with trees where a large part of the light is lost in the foliage.

The recommended spacing for side-street lanterns is 120 ft, and, while it would be an advantage to use a closer spacing, the cost makes it impossible in all but exceptional cases. Similarly any increase in the recommended mounting height of 15 ft would raise economic problems.

If, then, it is uneconomic to change radically the mounting height or spacing, the light distribution given by the lanterns is the only item which might be usefully changed. Some recent experiments have shown that such a change may be worth while.[9]

Side-street lighting is intended primarily for the pedestrian and householder. It is amenity lighting, not road lighting. However, although it is not usually possible to light the roadway sufficiently well for the motorist, some light must be allowed to fall on the road if only to maintain a cheerful appearance in the street. It follows that the whole area from one building line across to the other needs to be lit, including building faces, front gardens, pavements and roadway.

A symmetrical light distribution, which has occasionally been

used, is not very suitable since it produces 'cross-banding', i bright bands across the road opposite each lantern (a phen menon of perspective foreshortening and road-reflection chara teristics). It also causes bright patches on the houses near the lanterns. In addition, it can be very glaring to the motor if an attempt is made to produce uniform illumination, and, i tree-lined road, a considerable amount of light may be lost the nearest trees. Clearly the intensity in directions up a down the road and across it must be restricted.

Fig. 5 shows an installation in a short stretch of road usi experimental lanterns at the recommended 15 ft mounting heig

Fig. 5.—Experimental side-street installation using 150-watt tungsten lamps.

and 120 ft spacing. The light distribution from the lanterns shown in Fig. 6. This distribution was determined after considerable number of tests in which the intensities up a down the road and at right angles to it were varied over a wi range and in which the directions of the four main beams we also varied. The installation produced a uniform appearan without the objectional bright bands and patches and withou the large dark areas between lanterns commonly seen in si streets. The building faces, front gardens, pavements an roadway were well lit in spite of the large trees. The few tre shadows were considered to be in keeping with the charact of a tree-lined road and were never very dense, being reliev by light from other lanterns in the installation.

(6.3) Experiments in Installations

In addition to the formal experiments described a number lighting authorities, both here and abroad, have put up unco ventional installations which are well worth studying.

Fig. 7 shows an installation of wall-mounted lanterns usi 140-watt sodium lamps at 25 ft mounting height and 40 ft opp site spacing. The light is directed across the road so that fu advantage is not taken of the preferential reflection from t road. Nevertheless the installation is so generously planne that the amount of light—over 20 000 lumens per 100 ft—pr duces a result which rivals the best Group A installations. T absence of poles and the elimination of glare combine to produ an excellent result in a shopping area. It should be noted th the small spacing/height ratio (1·6 : 1 in each row) is necessa not only to provide the high level of lighting required but al to avoid cross-banding.

The use of columns for lighting a modern bridge is usua deprecated for aesthetic reasons, and a number of installatio
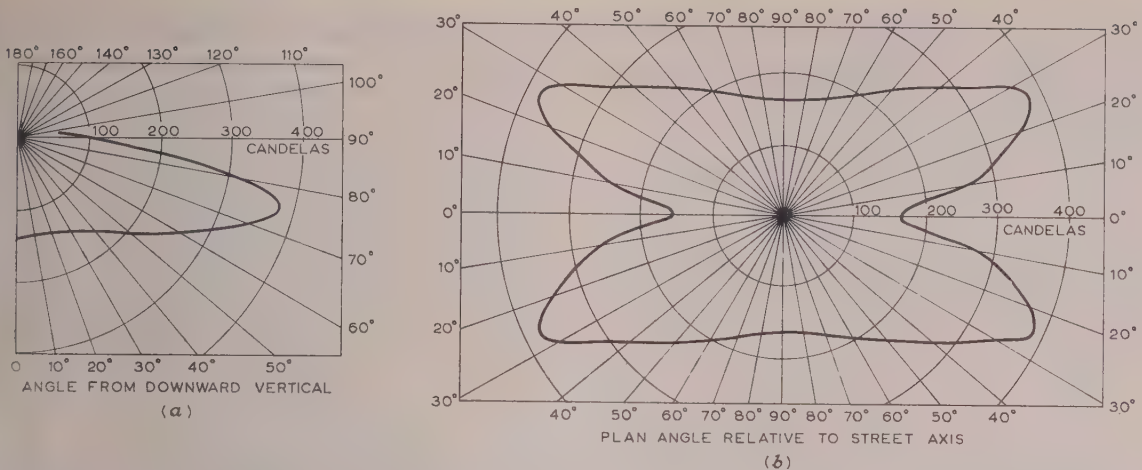
Fig. 6.—Light distribution from experimental lanterns used in Fig. 5.

(a) In vertical plane through the maximum intensity.
(b) Around lantern at 75° to downward vertical (conical).

Fig. 7.—Installation of wall-mounted lanterns.
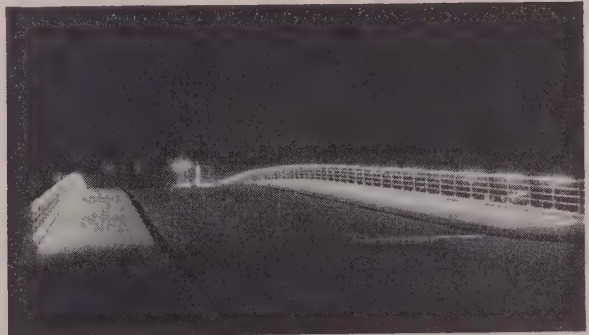
Fig. 8.—Bridge lighting installation.

Fig. 9.—63 kW lantern in Munich.

ing fluorescent lamps mounted in the handrail have been tried
the Continent. Fig. 8 shows a bridge at Dinant using
cold-cathode fluorescent lamps giving approximately 15 000
mens per 100 ft, or twice that for the highest recommended
el of Group A lighting. The lamps are shielded so that there
practically no glare, but the light is mainly directed on to the
otpaths to the detriment of the lighting on the carriageway.
esthetically it has attractions since there are no columns to
oil the line of the bridge, but the installation cost is high—some
times that of a conventional British Group A installation.
is shows something of the problem of lighting at low mounting
ights.

The lighting of large areas in cities has not received the
aginative attention which it sometimes deserves. However,
Munich[10] a huge lantern weighing 1·2 tons, housing three
kW xenon lamps and six 400-watt colour-corrected mercury
mps, has been mounted at a height of 100 ft to light an area
me 270 ft in diameter (Fig. 9). The total lamp light output
1·7 million lumens—enough to light four miles of road to our
andards. Although the erection and maintenance of such a
ntern poses some awkward problems, it is a neat way of lighting
large area without the clutter of columns which a conventional
stallation would demand.

(7) THE NEXT PHASE

The present state of street lighting in Great Britain may be
summarized as follows:

(a) The desire for good street lighting continues to grow both
among technical and lay people; as a result, more miles of road are
being lighted.

(*b*) However, the quality of lighting of individual roads (ignoring a few unusually good installations) has reached a plateau and is now falling rather than climbing.

(*c*) The main reason for this deterioration is that road surfaces designed for their skid-resistant properties are very difficult for the lighting engineer to handle.

(*d*) The situation is aggravated by the fact that we are not generous in the money allocated to street lighting.

(*e*) We can learn from practice oversea. In particular, the determination on the Continent to restrict glare has much to commend it.

(*f*) Our present Code of Practice is an excellent way of describing the parameters of the problem; in general, only the actual values given need modification. There seems little virtue in changing to the type of code adopted in some other countries.

(*g*) We have some useful experience from recent experiments both in the laboratory and in trial installations.

Technically, the key to improvement is obvious and fairly simple, namely a reduced spacing/height ratio. The present values of 5 : 1 or more cannot possibly provide good street lighting on present-day road surfaces. In particular, high-angle-beam lighting, commonly used with these large spacing/height ratios, is nearly always a failure on rough road surfaces. The surface itself tends to produce patch characteristics associated with cut-off lighting while high intensities emitted from the lanterns at high angles serve only to produce glare. The problem is less serious on the narrow winding road where light emitted at high angles falls on buildings and produces a sufficiently bright background to offset some of the effects of glare and where only two or three lanterns are visible at any moment. But on the long straight road, without a useful background, the glare can be intolerable.

Theory and practice show that a spacing/height ratio of 4 : 1 or less is essential, and in this respect Continental practice is better than that in Great Britain. A better ratio is best achieved by increasing the mounting height to 30 or 35 ft, thus maintaining the spacings substantially as at present and avoiding an increase in 'the forest of poles'. At such mounting heights, cut-off lighting becomes practicable at reasonable spacings and many engineers will demand it. However, many others, and perhaps the bulk of British road users, will still prefer to see some visible sources, provided that they do not dazzle. It would seem, therefore, that the medium-angle beam distribution, which not only gives some sparkle to the installation but is more flexible in layout, will have much to commend it. With either system, the intensities of light directed at high angles can be greatly reduced and the disadvantages of glare attributed to mercury sources will probably be negligible. This is valuable since it opens the way more clearly to the use of colour-modified mercury lamps.

As the geometry of the installation becomes more favourable to the designer, he can employ more powerful lamps and achieve higher illumination without discomfort to the road user. The situation and the path of progress is very like that already seen in interior lighting practice, the demand for more light forcing a need for better engineering practice. There is every reason to suppose that the public demand for better street lighting will persist, since nobody who has enjoyed good lighting willingly reverts to something worse.

The actual amount of light required is, of course, important, and a reasonable step up from present levels suggests that, for main roads, 10 000–20 000 lumens per 100 ft linear should be provided.

Side roads (Class B) also need more generous treatment than they usually get. Often they are the poor relation to be satisfied with a well-watered-down version of a main-road system. The experiment described in Section 6.2 suggests that other and better methods are possible and worth trying.

A light output of not less than 2 000 lumens and up to 5 000 lumens per 100 ft linear of road is desirable except in those places such as country lanes where only a few beacons of light are required. We must recognize that not all places are improved by being flooded with light.

In addition to these fairly obvious suggestions there is still great need for experiment. Much fundamental work is being done, particularly by the Road Research Laboratory, but more experiments are required in the street itself by practising lighting engineers. The bold way in which Continental engineers have tried unorthodox schemes such as extra high mounting and parapet lighting on bridges has taught them (and us) a great deal. Often the results have been as expected, but not always; sometimes the installations have been failures, but this does not necessarily mean that the experiment has failed. If our own experiments are crippled, either by their meagreness or by the fear of making mistakes, we shall certainly lag behind the Continent.

The Code of Practice for Street Lighting is now under revision and one subject the Committee is doubtless considering is the intermediate route, i.e. a class between main roads and residential roads. The present Code does not recognize such a special class, but the sharp distinction between Class A and B routes no longer seems justified. There are many roads in built-up areas which, although they are not traffic routes proper, now carry so much traffic that residential road (Class B_1 or B_2) lighting is inadequate; and there is much to be said in such circumstances for encouraging mounting heights up to 25 ft with a light flux of 5 000–10 000 lumens per 100 ft of road.

Among the other matters to be settled is the lighting of motorways. There are strong differences of opinion here. Objections are based largely on aesthetics, cost and the possible danger of having columns along a high-speed route. The bulk of informed opinion among technical people, however, is in favour of lighting. The problem is how best to do it. Among the possible methods are lighting from very short posts (an unlikely solution) or very high ones. The relative merits of cut-off, medium-angle beam and unidirectional distributions need to be determined in the particular condition of the motorway. The answer must be given finally by experiment on a substantial scale.

The major problem in such a programme is not technical but financial. Much has been squeezed out of little in this country, but unless we are prepared to spend more we shall fall not only behind other countries but also behind public opinion. The increase required is not great compared with the cost of building and maintaining a road. The installation cost of a typical present-day lighting system is some £2 000–3 000 per mile of road, which represents 2–3% of the cost of the road, and the running cost, including amortization, is some £700 per annum. Statistics suggest that the cost of lighting will be saved by reduction of accidents, quite apart from the saving of life and limb and making better use of our roads. Unfortunately our administrative system, with its emphasis on local authority rather than centralized control, spreads the load of costs in a peculiar way; perhaps, indeed, the problem is primarily one of administration.

This does not mean that a greater supply of money will serve as a magic wand making our difficulties vanish, but it is an essential requisite if we are to justify the boast which has so often been made, that the best street lighting in the world is to be found in Great Britain.

(8) ACKNOWLEDGMENTS

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DISCUSSION ON THE ABOVE PAPER

fore THE INSTITUTION 1*st December*, *the* EAST MIDLAND CENTRE *at* DERBY 1*st November*, *the* SOUTH MIDLAND CENTRE *at* BIRMINGHAM 7*th November*, *the* SHEFFIELD SUB-CENTRE *at* SHEFFIELD 16*th November*, *the* NORTH STAFFORDSHIRE SUB-CENTRE *at* CREWE 28*th November*, *and the* NORTH-EASTERN CENTRE *at* NEWCASTLE UPON TYNE 12*th December*, 1960.

Dr. J. W. T. Walsh (*at London*): The authors have made it ar that until quite recently street lighting in this country was gely dominated by the Code of Practice, which, in its turn, s really drawn up to standardize the recommendations of the partmental committee. That committee reported in 1937. nsequently, it is not surprising if we now find that much of e present Code needs modification.

The cost of the light itself on our roads is in real values only out one-twentieth of what it was in 1937. Since then, the affic conditions and the roads themselves have vastly altered. Furthermore, the nature of the road surfaces, which is very portant from the street-lighting point of view, has undergone ofound modification. Thus much new thinking is needed th regard to the best way to light our streets.

I am glad that such emphasis is placed on spacing/height ratio. here are two principal criteria in street lighting, namely the nount of light delivered to the street and the spacing/height tio. In the Code of Practice, as in the recommendations of e departmental committee, the spacing/height ratio came in a consequence of recommendations on height and spacing parately. The other important factor, namely street width, as not dealt with in a very satisfactory way. However, it has very profound influence and, in my opinion, determines the ounting height. The quality of the street-lighting installation then determined by the spacing/height ratio.

The figure of 4 : 1 was mentioned for this ratio. In 1892 . P. Trotter when talking about street lighting—in the City of ondon it is true—recommended a spacing/height ratio of 4 : 1, nd now 68 years later we are still talking about a ratio of : 1. It is time we made some advance in this matter.

As the authors state, the problem is not technical but mainly nancial. It seems extraordinary that, with the present much wer cost of light, we should be progressing so very slowly. ne of the factors is, of course, the extraordinary financial rangements for paying for street lighting. A main road rrying bulk traffic may pass through a little parish where it ould cost perhaps a 5s. rate, to provide a satisfactory standard lighting. I hope that obstacles like these to good street ghting will soon be eradicated. One of the main complaints motorists about street lighting is the extraordinary multi-icity of standards of lighting through which they have to avel. The motorist does not mind going from one good ghting system to another, but he does object to going suddenly om an extremely good system into something which is

extremely poor, and then back again to something entirely different.

Mr. H. R. Ruff (*at London*): While the authors' demonstration of the reduced glare from sodium light, using high-brightness panels of equal luminance of sodium and mercury light, might suggest that greater glare from mercury installations is mainly due to this factor, our own studies suggest that, in practice, the major factor is the polar distribution of light from the lanterns. When we made special mercury lamps to give exactly the same light output from the same source size as 140-watt sodium lamps, then used them in identical optical systems and carried out a subjective survey in which members of the Road Research Laboratory and Road Research Board were able to join, the result was that 50% considered mercury to be more glaring and 50% found no difference. Thus, while we would agree that there is some advantage in the sodium colour, is not the factor rather small?

Our studies suggest that, while at a high road brightness of 1–2 ft-lamberts the subjective brightness of sodium and mercury light is closely related to the luminance, mainly owing to the Purkinje effect, for very dark objects or shadows on roads, sodium luminance needs to be increased up to six times before matching that object lit by mercury light. The rather increased contrast is probably a main factor leading to some European suggestions that the ratio of mercury light to sodium light needs to be 1·6 : 1 to give the same visibility under street conditions.

The authors, while suggesting higher mounting heights and more light per point, made no reference to the introduction of higher-lumen sodium lamps in this country by 1959. Many street lighting engineers have now tried these new sources particularly for wider roads. The modern rough road surfaces had already rendered high-angle-beam lanterns too glaring to be satisfactory, but did not the lowest-price-tender limitation tend to squeeze medium-angle-beam lanterns dangerously close to the upper specification requirements? In the revolution from high-angle-beam lighting glare there could be a danger of this country swinging to too severe a cut-off system when Continental practice seems to be favouring some relaxation. We had the pleasure of inspecting high-power sodium lighting installations with some Continental friends; they considered that, with the good medium-angle-beam lanterns used, the glare was satisfactory and the lighting good, and I think that the differences between European and British practices are rapidly diminishing.

Mr. H. Jackson (*at London*): In Section 7 the authors give

the cost of a typical present-day lighting installation as £2 000–£3 000 per mile of roads. I assume that this refers to Class A lighting and that it is for a single carriageway.

I should like to give some details of a 35 ft mounting scheme which was installed about a year ago on a length of about two miles of dual-carriageway road which is a bypass through one of the suburbs of Cardiff. The actual length is 1·93 miles. The lighting units are 200-watt sodium lamps in medium-angle lanterns, and the lanterns are inclined at about 10° above the horizontal in order to improve the light distribution across the width of the road. The spacing averages 160 ft, which, with a mounting height of 35 ft, gives a spacing/height ratio of 4·5 : 1, and the light output is 9 600 lumens per 100 ft linear. The total cost of this installation, which is for a dual-carriageway road, was £11 700. This is almost exactly £6 000 per mile, or, if one thinks of the single carriageway, £3 000 per mile, which is the same as the upper figure given in the paper.

The running costs of this installation—energy and maintenance only—amount to £790 per mile per annum. The energy component of these charges is based on known costs, but the maintenance component is a pure estimate since it is the first installation of its kind in the South Wales area. The charges may well be subject to alteration in due course when we know the actual cost of maintaining the installation. The maintenance of these 35 ft columns involves the provision of hydraulic platforms, which are larger and more costly than those used hitherto.

As a user and a motorist, I consider this to be one of the best, if not the best, installations that I have experienced in this country or, with a somewhat limited experience, on the Continent. The absence of glare is quite remarkable, and the ease with which one sees objects in silhouette when driving on either a wet or a dry road surface has to be experienced to be believed. I might add that the surface is a rough one. Any expenditure to raise the light output to the figures mentioned in the paper, namely between 10 000 and 20 000 lumens per 100 ft linear, would scarcely be justified.

Mr. G. F. Freeman (*at London*): I am interested to learn from Dr. Walsh of the way A. P. Trotter had anticipated one item. A sodium-lighting scheme with central supports was first introduced into this country by the Liverpool City Engineer, Mr. Robinson, about 25 years ago. I believe that it was a very successful system, and Mr. Robinson had both faith and vision. I am extremely glad to see the progress that sodium lighting has made since then, as I have been convinced for many years that it is the scheme *par excellence* for street lighting.

Mr. S. S. Beggs (*at London*): We cannot have good street lighting unless we pay for it. It is for members of The Institution to use their influence with lighting authorities upon every occasion to get them to spend adequate amounts for this purpose.

With regard to light sources, I found it difficult to fill in the questionary, because there were two plain questions and I wanted to qualify them. A poll like this can be misleading. I appreciate that considerable experimental work has been done quite apart from the poll, but I believe that most of it was with sodium and plain mercury lamps. Do the authors' comments under 'mercury' apply to the tubular fluorescent and high-pressure fluorescent sources? It would be very wrong to leave the impression that 'mercury is bad' by lumping the sources together, when there may be very great differences between different mercury sources.

In Fig. 4, the smooth surface corresponds to a luminance factor of about 50 and a sideways-force coefficient of about 0·2, whilst for the rough surface the luminance factor is about 5 and the sideways-force coefficient is about 0·9. On the graph relating luminance factor and sideways-force coefficient, these points are rather at the extreme ends of the line. I believe that

a sideways-force coefficient of about 0·5 is quite good. Are w[e] perhaps not putting all our weight on having non-skid surface[s] and forgetting that we must be able to see well at night? Ther[e] is a range of materials which would provide a sideways-for[ce] coefficient of 0·5 or 0·6 and a luminance factor of 20–25, an[d] would be satisfactory. Has sufficient attention been paid t[o] intermediate surfacing materials?

Mr. G. K. Lambert (*at London*): I should like to raise th[e] subject of an intermediate level of lighting for roads which a[re] not traffic routes and classified as such, but which have to carr[y] much local traffic and may be bus routes. There is a good de[al] of 60-watt sodium lighting at the 15 ft mounting height, and [it] is satisfactory for the level of traffic which these roads have t[o] carry, but now that the mounting height on main roads is bein[g] increased to 35 ft, do the authors not think that there is a goo[d] case for increasing the mounting heights on the side roads?

Mr. J. M. Waldram (*at London*): Dr. Walsh raised the questio[n] of the Code of Practice for Street Lighting and mentioned tha[t] it was being revised. It is, of course, impossible to say exactl[y] what the committee will do, but they are considering a number o[f] the points which have been raised in the discussion, including th[e] question of greater mounting height and smaller spacing/heigh[t] ratio, and the question raised by Mr. Lambert. I do not kno[w] how long it will take to prepare the new Code, but the work i[s] going ahead and we are trying to keep in step with moder[n] developments.

It should be said that the old Code was a very good on[e]. It stood for about 25 years before modern practice caught u[p] with it, and that is not a bad record. If it now has to be revise[d] it is gratifying that we do not have to revise it so very much i[n] the light of the developments which have taken place since i[t] was first prepared.

Mr. F. C. Smith (*at London*): It was recognized at the Con[-] ference of the Association of Public Lighting Engineers held i[n] September, 1960, that many of the conditions which determin[e] the standard of public lighting necessary to the expeditious an[d] safe movement of traffic at night are changing and becomin[g] perhaps more complex.

It is evident, to name only two of these changes, that importan[t] alterations in road layout and dimensions are occurring i[n] order to facilitate the movement of the ever-increasing vehicula[r] traffic, and that road surfaces having improved non-skiddin[g] properties but of inferior lighting characteristics are ver[y] properly coming into use. These and several other factors hav[e] to be recognized if the known correlation between accident ris[k] and standards of public lighting is to be applied to the benefit o[f] all road users.

The changes which affect the standard of public-lightin[g] requirements and design are occurring with ever-increasin[g] rapidity, and the synchronization of the rapidity of these change[s] brings about a sense of urgency which can only be ignored wit[h] the acceptance of increased accident risk and the retarding o[f] traffic movement. In my opinion, the authors have no[t] emphasized sufficiently the importance of the rapidity of th[e] changes which are occurring.

The research workers and development engineers have don[e] much to put new 'tools' into the hands of the public lightin[g] engineer. The research laboratories have made available ne[w] and more efficient sources of light and brought into being ne[w] materials having properties peculiarly suited to public-lightin[g] requirements. These are among the assets which make it possib[le] for the lighting engineer to tackle with confidence the problem[s] associated with the 'changing scene'.

Mr. G. C. Small (*at Derby*): The authors refer to Group [C] street lighting as being something of a Cinderella, but in certai[n] cases, the description is general. For instance, in the tow[n]

here I live the rate levied in respect of public parks exceeds 1d., for libraries, museums and art galleries it is 9¾d., and yet at for public lighting is only about 6¼d.

In referring to Group A lighting, the authors quote from the British Standard Code of Practice, which states that the average acing should be 120 ft where the lamps are mounted 25 ft ove ground. I would welcome their views on the desirability reducing this spacing to 110–115 ft where the lighting is on open road and there is no reflection from buildings.

The authors also state that cut-off lighting costs approxiately 20% more than non-cut-off lighting. Do these figures late to amortization on capital expenditure only, or are they clusive of maintenance?

On the question of the experiments being carried out by the oad Research Laboratory, I should be interested to know hether they are on a normal road or the perimeter track of an d airfield. If they are on the latter, it would seem desirable for ere to be some form of 'Hollywood set' of the facade of uildings, so that the reflection factor, etc., can be gauged.

Quite an appreciable number of installations are now coming ito commission in this country with a mounting height of 5 ft, and this has presented problems to those responsible for aintenance, since the majority of tower wagons only extend 25 ft. Do the authors visualize 35 ft as the ultimate for this ountry, or are we likely to see 40–46 ft within, say, the next n years?

The installations in Germany and elsewhere on the Continent f lanterns mounted at 80–100 ft would seem undesirable in reat Britain, not only in view of the severe fogs experienced in e winter but also owing to difficulties of maintenance.

I would also appreciate the authors' views on the lanterns at xtremities of installations being of the cut-off type. Experients in the East Midlands make it appear that such an arrangeent is desirable, since anyone driving out of the installation is orced to switch on his headlamps, whilst those driving into it re not troubled with glare until their eyes have become attuned o the installation.

Mr. H. L. Jones (*at Derby*): With the present tendency to use ough and darker road surfaces, silhouette vision becomes more ifficult and direct lighting would be more satisfactory. This s emphasized in Fig. 4, where the distant columns are seen light gainst the dark background. Moreover, direct lighting is ssisted by any vehicle lighting which tends to counteract ilhouette. More use should also be made of 'cut off' lighting o reduce glare and increase visibility. The so-called 'tunnel ffect', far from being a distraction, is really an aid to vision as t concentrates attention in the right direction.

I disagree with the authors' statement in Section 3.1.2.5 that colour is of little importance to the driver'. Colour requires nore consideration, and we must look beyond sodium and nadequately-corrected mercury-vapour lighting, which are both nakeshifts of the past.

There have been recent suggestions for lighting the new notorway M1. If there is capital available it should be spent on ringing up to the standards now possible the lighting of our ll-purpose main roads through built-up areas. Much of it is nsatisfactory and more totally inadequate. Meanwhile safety vould be ensured on M1 and the trunk roads through open ountry by the enforcement of efficient anti-glare headlamps on ll road vehicles.

The code for side-street lighting must also be revised, with mphasis on increased mounting height and better lanterns.

Mr. M. L. Howe (*at Derby*): I would like the authors' views n the 'hotch potch' installations which arise when several local ghting authorities have control over a stretch of main Class-A oad, but not, of course, trunk road. I have in mind a par-

ticular section of road approximately 1½ miles long, unlit until recently, which was 'adopted' by the appropriate rural district council as the lighting authority. The adjoining sections of road at either end are lit by a Group-A fluorescent installation and an older Group-A mercury scheme, respectively, under two other lighting authorities. The central section has now been lit by a Group-A sodium installation, mainly on the advice of various independent road safety committees were who apparently not aware of the location. The result is most disconcerting to the motorist.

I would also appreciate the authors' views on the relative merits of the various types of lighting under fog conditions.

Mr. S. F. Adcock (*at Birmingham*): The question of cost appears throughout the paper, and it is stated that the purchaser of a road-lighting installation must decide how much he is prepared to pay for certain features and to what extent he can compromise between them. The cost of street lighting is only a very small proportion of the total cost of a highway—its construction and maintenance—and one should not have to compromise at all, so far as cost is concerned, over fundamental factors that go to make up a good installation. Lighting is so important from the point of view of accident prevention, amenity value and security that the general clamour for improvement must be met irrespective of cost, within reasonable bounds.

It is stated in the paper that on the Continent they are sensitive to glare whereas in this country we are over tolerant. I am surprised that, later in the paper, it is stated that the bulk of British road users prefer visible sources of light, provided that they do not dazzle. A lighting installation I know makes me doubt this statement. The installation utilizes full cut-off lanterns, with no light above the horizontal. However, the road surface does not 'play' particularly well, with the result that there are considerable areas of shadow and patchiness. The public are quite obviously pleased with the installation, and I believe that a lower level of illumination on the road surface could be tolerated, provided that there was a total absence of glare.

If this were agreed, I am quite sure that, in this country, we must move much closer to the Continental practice, even if it means the closer spacing of lanterns.

In Section 7 it is stated that there is probably a need for an intermediate standard of lighting between the accepted Groups A and B. Although it is technically possible to introduce another grade, in view of the present system of finance of lighting and the usual shortage of money from local authorities, I feel sure that this intermediate grade would be utilized in thoroughfares which justified Group A treatment. I would rather see a more generous interpretation by local authorities of the term 'traffic route'.

The authors mention the importance of imaginative treatment, and they show some very fine examples, particularly Munich and the bridge at Liége. There are many problems, particularly in a city with congested junctions and thoroughfares which are overburdened with traffic. Many cities are now involved in planning underpasses, overpasses and elevated roadways. These projects have to be tackled in an imaginative fashion, and much work must be done if the lighting is to be attractive and efficient.

Mr. E. C. Cooper (*at Birmingham*): One of the principles in the design of street lighting is to mount the lantern over the kerb. I suggest that the back of the footpath might be a much better position. Moving the lantern away from the axis of the road would, unless lantern light distribution were altered, tend to light the footpath and buildings at the expense of the road, but experiments described by Mr. Waldram at the recent Conference of the Association of Public Lighting Engineers indicated

that this might be a reasonable thing to do. The driver naturally attaches as much, if not more, importance to things on the footpath as on the road, and furthermore the limitations on surfaces favourable to street-lighting design do not apply as much in the case of footpaths as they do in the case of roads.

A further point in the design of street lighting is to avoid siting the lanterns so that they give a misleading indication of the direction of the road.

Street-lighting design is more complicated than most engineers realize, and it should be more widely taught in technical schools. Moreover, its development depends to a large extent on site experiments. Continental authorities appear to be in a good position to undertake such experiments, and it may be that street lighting should be organized on a comparable basis in this country.

Mr. L. L. Tolley (*at Birmingham*): The authors state that a mercury-vapour lamp of a certain brightness looks brighter than a sodium lamp of the same brightness. I believe that daylight contains more power in the yellow than in the blue part of the spectrum, and it might therefore be expected that a certain power in yellow light would not look so bright to us as the same power in blue light, because we are not so used to the blue light. I find that patchiness, as one comes under the light and then moves away from it, is the worst fault in street lighting. The authors state that the best visibility is obtained by silhouette vision. When car headlamps are on, objects are seen by reflected light. On an unlit road I would switch on my headlights, and although they do not give 2 000 lumens per 100 ft, I would feel more comfortable than driving along some urban lighted streets. I suggest that road lighting might be arranged in a manner similar to headlamps pointing in the direction of traffic flow. This would, of course, be difficult to arrange for a street carrying traffic in both directions, but it should be possible for double-track roads.

Mr. J. Terry (*at Birmingham*): Most of the illustrations in the paper are based on discharge lighting with one or two incandescent installations employing the same type of energy source. What is the present situation with incandescent lighting employing the alternative form of fuel?

The high-pressure installations that were introduced just before the war appear to be disappearing. Is this due to economic reasons, and, if so, are any developments envisaged that would permit the re-entry of this form of illumination into the field of street lighting?

Mr. G. E. Kemp (*at Birmingham*): In my town until quite recently 18–20 ft columns were common. In spite of the use of specular reflectors, to the best of my knowledge there have been no road accidents of any consequence on roads lit by this means.

Do statistics of accidents after dark differentiate between 15 and 25 ft street lighting? Is the 15 ft column the cause of many accidents? It rarely provides good street lighting, and the lantern has a high glare factor, being perhaps only 8 ft above the eye level of bus and lorry drivers.

Concrete 15 ft columns are unsightly, but aluminium is now coming into use, and we could have slender columns like those made of steel, but with reduced corrosion troubles. 20 ft columns could well be used on the majority of these roads, and they could be reasonably unobtrusive if of slender design.

Mr. J. V. Peacock (*at Birmingham*): In my experience on well-lighted roads objects frequently reflect more light than the road surface, and I doubt the statement that on such roads one sees by silhouette vision. The illustrations show empty roads, and they would have been improved by the inclusion of several objects. I do not agree with the statement in Section 2.1 that

objects on a road by day are commonly seen to be darker than their background.

Dr. O. I. Butler (*at Sheffield*): Occasionally, in my otherwise well-illuminated road, there is little or no suggestion of any line of demarcation between the road and the very wide pavement. This presents quite a hazard on a bend in the road, and I should be interested to learn of the steps taken generally to eliminate this.

Mr. M. M. Macmaster (*at Crewe*): The ultimate criterion of the merits of any lighting system is its effect on the human eye. Manual response to visual perception varies up to $\frac{1}{2}$ sec in the case of middle-aged persons. The corresponding distance travelled at 30 m.p.h. would be 22 ft. The period of colour persistence is usually greater than that of intensity appreciation, and might involve risk at a point of abrupt change in source colour along a roadway. One method of minimizing this defect would be to intersperse lighting units of different colour, to the extent of two or three fittings on each side of the point where change in source colour was deemed to be expedient.

Mr. R. H. Gregory (*at Newcastle upon Tyne*): I sometimes think that the present Code of Practice has inadvertently discouraged better lighting in Group B by fixing the mounting height at 15 ft with tolerance of +1 ft. There are many cases where a 17–18 ft mounting height could be used to advantage with very little extra expense. For example, in an area which is being redeveloped, the pattern of side-street use both by pedestrian and motorist tends to change. What were comparatively quiet streets become minor traffic routes and short cuts between major routes. The question of relighting then becomes a problem. Should they remain Group B or become Group A? Given a well-planned 15 ft mounting-height installation it is a cheap and easy matter to fit a long bracket suitable to take the lower-power sodium or colour-corrected mercury-vapour discharge lamp and lantern to produce an installation which lights the road adequately and provides about 3 000 lumens per 100 linear ft of road, which is too high for Group B at 15 ft mounting height but inadequate for Group A at 25 ft. With 17 ft or more mounting height the lantern can overhang the road and allow a bus to pass underneath—in fact, I have used a bracket with a 6 ft out-reach at this mounting height on a tree-lined road as an alternative solution to the problem discussed in Section 6.2. Furthermore, the spacing/height ratio is reduced and I have found that the damage to lanterns from vandalism is materially reduced. This system can also be used to advantage on bus routes through residential districts. Another problem in the older residential districts is the variation in the width of the street, which may be anything from 12 to 32 ft. One simple solution which assists in producing a more uniform standard of lighting is to measure 120 ft spacing diagonally across the road between staggered lamps. This, of course, reduces the spacing in proportion to the road width, and, in turn, reduces the spacing/height ratio.

In my opinion, an increased tolerance of +2 or 3 ft on the 15 ft mounting height and raising the limit of the total luminous flux emitted from the lantern from 2 500 to, say, 3 500 lumens per 100 linear ft of road would encourage improvements in the lighting of side streets at very little extra cost.

Messrs. W. R. Stevens and **H. M. Ferguson** (*in reply*): Dr. Walsh mentions a recommendation for a spacing/height ratio of 4 : 1 which was made as long ago as 1892. There is some evidence that we are now approaching this value, but a bitter rearguard action is being fought by some who regard good street lighting as unnecessarily expensive. We are grateful to Dr. Walsh for reminding us of the immense drop in the cost of light since 1937, and to Mr. Small for pointing out that street lighting often takes second place to public parks, libraries, etc.

arsimony seems hardly justified in a public service which is concerned not merely with amenity but also with life and death. Mr. Jackson gives some interesting details of a dual-carriageway installation which appear to support very well the figures for cost quoted in the paper for a single carriageway. However, it is a common fallacy to suppose that tilting the lanterns 10° or so will produce a significant improvement in performance on the roadway, though the daylight appearance may well be improved. A tilt of 45° would be worth while, but this would reduce the light on the footpaths and surrounds, which, as Mr. Cooper points out, is undesirable. Indeed we need more light on the surrounds, and this suggests that we not only want much more light from the lanterns but that we need to control it more carefully. Perhaps the 4-beam light distribution shown in Fig. 6 could be applied to main roads.

Both Messrs. Jackson and Small mention the problem of maintenance of high mounted lanterns. This is something which has to be faced. On the Continent they have been doing it for many years.

Mr. Freeman's preference for sodium lighting is shared by a majority of motorists, and, while we are very sympathetic with Mr. Jones's comments, we are still inclined to the view that colour *per se* is of little importance to the motorist.

Mr. Beggs draws attention to the questionary on mercury and sodium lighting which the audiences were asked to fill in. We did not read too much into the results, for the reasons which Mr. Beggs has given. Nevertheless it is interesting that the results up and down the country show a marked preference for sodium lighting, the percentage voting in favour of sodium varying from 65% to 95%. Voting on the question of glare reveals that between 60% and 90% find mercury more glaring than sodium.

The reason for these results is complex. It is due in part to the greater glare from a high-luminance mercury source compared with a similar sodium source of the same high luminance. We do not agree with Mr. Ruff that this factor is small. At least two observers out of three condemn mercury lighting on the score of glare for this reason alone. However, as Mr. Ruff points out, many other factors are involved. Again, we doubt very much whether his explanation of the superior performance of sodium lighting reported from the Continent is valid. One of the results of the Dutch experiments is that a sodium installation gives a better apparent uniformity of road brightness than a similar mercury-fluorescent installation. Our own experiments support these results, which run counter to Mr. Ruff's statement. However, we must make it perfectly clear that we are not arguing in favour of sodium as the best of the many sources available for street lighting.

Messrs. Lambert, Gregory and others raise the question of an intermediate category between Group-A and Group-B lighting with mounting heights up to about 20 ft. There is much to be said for this, provided that we take seriously the warning given by Mr. Adcock. It must not become an excuse for degrading main-road lighting.

Mr. Waldram states that the old Code was a very good one. We agree, but it is now well out of date. Mr. Smith emphasizes the rapidity with which changes are occurring, and we believe that it is a matter of urgency that a revised Code be made available even if it is not perfect in every detail.

The validity of silhouette vision in lighted streets, particularly with modern dark surfaces, is questioned by Messrs. Jones, Tolley, Peacock and many others. Space does not permit an exhaustive comment, but the situation, briefly, is that the majority of objects in the majority of positions in which they occur on the road appear darker than their background. As the roads become rougher and darker, and as vehicles and other objects become lighter in colour, 'reverse silhouette' occurs more frequently. However, at the present time this change has not gone so far (and it may never go so far) that silhouette vision does not predominate with conventional street lighting, as it does, for the most part, by day. We can all think of occasions and places where the 'rule' is broken, but they are still in the minority.

Mr. Jones favours cut-off lighting and the 'tunnel' effect. Few will disagree with him on the open road but many view with disfavour the effect of cutting off buildings at lantern height in cities and towns. Mr. Adcock also favours cut-off lighting, and, like many, is prepared to forgo some road-brightness uniformity in exchange for complete absence of glare. However, this should not be carried too far, and we must accept the fact that we cannot expect to have Continental lighting (even if we want it) while we are only prepared to pay a British price. We agree with Mr. Ruff that genuine medium-angle-beam lighting can be very good, but that it has been bedevilled by the curse of the lowest tender. It is commonly believed that medium-angle-beam lighting can be had as cheaply as high-angle-beam lighting. This is blatantly untrue and largely accounts for the fact that very little genuine medium-angle-beam lighting is to be seen in this country. It has not been given a fair chance. We agree entirely with Mr. Jones that we need better lanterns: the problem is financial, and not technical.

Mr. Howe's comments on 'hotch-potch' installations underline the administrative chaos that exists in street lighting up and down the country. We need a uniform high standard of lighting, though we should not necessarily insist on complete uniformity of lamp, light distribution, etc. 'Variety is the spice of life' if it is kept within sensible bounds. We are interested in Mr. MacMaster's suggestion for mixing two adjacent installations for a short distance where the change-over takes place, and we like Mr. Small's proposal to use cut-off lanterns at the end of an installation. Both should be tried.

Mr. Howe and others refer to the relative merits of different light sources in fog. As far as is known, there is nothing to choose between them, though many claim that sodium lighting seems preferable. It is almost certainly a psychological effect; perhaps the warmth of the colour seems more friendly in adverse conditions. Certainly there is no greater 'penetration' of fog with sodium lamps compared with other sources.

In reply to Mr. Kemp, we have no accident statistics for Group-B installations, but we feel sure that the level of lighting deserves to be increased by a factor of two or three. This would almost certainly solve the problem of differentiation between pavement and road raised by Dr. Butler. Higher levels of lighting will, of course, produce more glare unless we adopt a light distribution with restricted intensities near to the direction of the roadway (see Fig. 6). The spacing between lanterns should also be reduced, particularly in wide residential roads, as suggested by Mr. Gregory.

THE DETERMINATION OF THE ELECTRICAL CHARACTERISTICS OF AN ARC FURNACE

By J. RAVENSCROFT, B.Sc., Associate Member.

SUMMARY

The paper describes three different methods for the determination of the electrical characteristics of arc furnaces. A comparison is made between the three methods by applying each in turn for the determination of the electrical characteristics of a 10 cwt Héroult-type 3-phase arc furnace.

In the first method the characteristics are obtained directly from observations on the furnace during normal operation and under short-circuit conditions; in the second method the furnace curves are calculated by using an equivalent circuit for the 3-phase arc furnace; the third and most simple method treats the furnace as a balanced 3-phase load and utilizes a current-locus diagram to calculate operating points on the characteristics.

For the 10 cwt furnace the simple locus-diagram treatment gave results of sufficient accuracy for all practical purposes, and the characteristics show that the furnace is most efficient, electrically, when operated on the highest voltage tapping.

LIST OF SYMBOLS

V = Line voltage.
V_1, V_2, V_3 = Phase voltages.
I_1, I_2, I_3 = Phase currents.
I = Current when three phase currents are equal.
I_{max} = Current corresponding to maximum circuit power.
P_T = Total circuit power.
P_1, P_2, P_3 = Phase powers.
P_{Tmax} = Maximum circuit power.
R_1, R_2, R_3 = Fixed phase resistances.
R_{A1}, R_{A2}, R_{A3} = Arc equivalent resistances.
R'_1, R'_2, R'_3 = Total phase resistances.
$R = \Sigma R'_n/3$.
X_1, X_2, X_3 = Phase reactances.
$X = \Sigma X_n/3$.
Z_1, Z_2, Z_3 = Fixed phase impedances.
Z'_1, Z'_2, Z'_3 = Phase impedances including the three arcs.
Z_a = Total circuit equivalent impedance.
k = Transformer turns ratio.

(1) INTRODUCTION

A comprehensive study has been made of the electrical characteristics of the 10 cwt experimental arc furnace at the Sheffield laboratories of the British Iron and Steel Research Association (B.I.S.R.A.). Three different methods for the determination of arc furnace characteristics have been considered, namely

(a) Direct determination from observations obtained during normal operation of the furnace and under short-circuit conditions.
(b) Calculation, by the use of an equivalent circuit for the 3-phase arc furnace.
(c) Calculation, by treating the furnace as a balanced 3-phase load and using a current-locus diagram to represent the furnace circuit.

Mr. Ravenscroft is with Steel, Peech and Tozer, and was formerly with the British Iron and Steel Research Association.

(2) DESCRIPTION OF THE EXPERIMENTAL ARC FURNACE

The B.I.S.R.A. arc furnace[1] is of 10 cwt nominal capacit and is powered by an 11 kV 500 kVA transformer. There ar four voltage tappings on the primary of the transformer, and by connecting the windings in delta or star, eight different voltage are available at the furnace electrodes, ranging from 64 t 180 volts on open-circuit. The secondary windings are delta connected. Incorporated with the high-voltage windings of th transformer is a tapped reactor, and the supplementary reactanc on each voltage tap can be varied from zero to 33%, at rate full load current, in three equal steps. The total impedance o the transformer and the reactor on the highest voltage tap i about 40%.

The instrumentation of the furnace consists of a voltmeter, a ammeter, a power-factor meter and an integrating kilowatt-hou meter on the primary side of the transformer, and three ammeter (one in each phase), a voltmeter and a wattmeter on the furnac side. A recording wattmeter and a triplex recording ammete are also connected at the electrode holders.
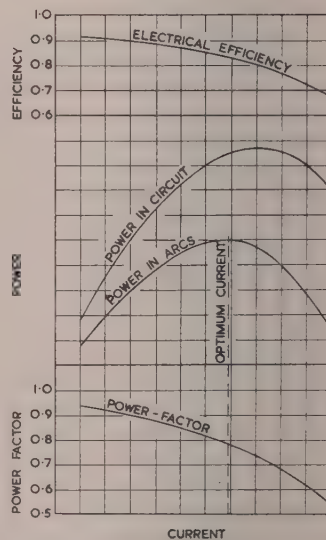

Fig. 1.—Typical electric-arc-furnace characteristics.

(3) ELECTRICAL CHARACTERISTICS OF AN ARC FURNACE

The electrical characteristics of an arc furnace (Fig. 1) ar such that for any given voltage tap the power input to th furnace transformer (hereafter called the 'circuit power') increase as the electrodes are lowered to increase current, then levels o and finally decreases as the arc current is further increased. Th

eful power input, i.e. the power dissipated in the arcs, also increases at first with an increase of current, and the arc-power/furnace-current characteristic lies below the circuit-power curve, reaching a maximum at a current slightly less than that corresponding to maximum circuit power. The peak in the arc-power characteristic represents the highest useful power which can be put into the furnace on the given transformer voltage tap for those circuit conditions, and the current corresponding to maximum arc power is usually termed the 'optimum current' for that particular voltage.

If it is considered that all the electrical energy dispersed other than in the three arcs does no useful work, the electrical efficiency of the installation is given by the ratio of arc power to circuit power. A certain amount of the power dissipated in resistance heating of the electrodes inside the furnace could be classed as doing useful work, since it will help to heat the furnace refractory lining and so reduce the energy absorbed in the lining from other sources. However, since it would be difficult in practice to estimate the amount of useful heat produced in the electrodes, the expression given for electrical efficiency is generally used as a basis for comparison between different furnaces and does not introduce any serious error.

For a given transformer secondary voltage the electrical efficiency of the furnace decreases steadily with increase of furnace load, falling off rapidly after the arc power has reached a maximum. The overall circuit power factor also falls steadily with increase of load, and its minimum value corresponds to zero arc power and maximum furnace current, i.e. when the three arcs are short-circuited.

.1) Direct Determination of the Circuit-Power Characteristic

During the early stages of the melting or 'breaking down' period the arc furnace represents a very fluctuating electrical load, and any determination of the electrical characteristics of the furnace must thus be made when the metal is completely molten and the load is much steadier.

Circuit power can be measured directly if the furnace is provided with an indicating wattmeter on the h.v. side of the transformer; otherwise supplementary wattmeters must be used. Alternatively, when conditions are steady and the electrode current in each phase is remaining constant, the average power input can be determined by using the furnace kilowatt-hour meter to integrate the energy consumed during a definite time interval.

It is usual to plot circuit power, electrical efficiency and power factor against mean current measured on the primary side or the secondary side of the furnace transformer. The changes in electrical performance on different voltage taps are best illustrated by plotting the variables against electrode current, but it is advisable, when measuring the current, to use those instruments which give the highest overall accuracy when the relative instrument transformers are included.

For the 10 cwt furnace the characteristics were plotted against the mean electrode current because the furnace is fitted with a special set of double-range class-B current transformers on the secondary side of the transformer and the three indicating ammeters are of first-grade accuracy. Power was measured by using supplementary wattmeters of substandard accuracy.

The curve showing the relationship between circuit power and furnace current for a given transformer output voltage was obtained as follows. The 'load regulator', which presets the working current of the electrode regulator at the desired level by balancing a voltage signal proportional to the electrode current against the corresponding arc voltage (impedance control), was set to give the minimum current for stable arc operation and the necessary readings were taken. Subsequent

values were obtained by varying the current with the load control.

If the furnace load regulator is correctly adjusted, the highest load tap should correspond to the transformer full-load current or slightly above on the higher voltage tappings. The results so determined will only give the lower portion of the power input curve. However, in practice it is usually possible to modify the control settings to give currents up to about 170% of the normal maximum working value for short operating periods, to enable experimental results to be obtained. If the current corresponding to maximum circuit power can be reached or exceeded by this method, a fairly accurate power curve can be drawn.

The circuit-power curve on the No. 5 (110-volt) tapping illustrated in Fig. 2 was determined by the above method. In this case all the supplementary reactance was in the circuit and the equivalent furnace impedance was $56 \cdot 5\%$. An important extra point, C, on the characteristic was determined by performing a short-circuit test on the furnace.

(3.2) Making a Short-Circuit Test

To carry out a full short-circuit test on a 3-phase arc furnace, the three graphite electrodes must be short-circuited at their tips. Obviously, the best way to conduct such a test is by short-circuiting the electrodes in a bath of molten steel. Prior to the test the electrodes should be adjusted in the clamps so that the lengths of the three columns inside the furnace are approximately equal. The procedure is as follows:

(a) Switch on the furnace at the desired voltage tapping and allow the regulator to adjust the electrodes until three steady arcs are obtained.
(b) Lower the electrodes, each at the same speed, until the ends are just immersed in the molten bath.
(c) As soon as the meter readings reach a steady value, note the observations and raise the electrodes clear of the bath.

It is essential to observe all the meter dials quickly and simultaneously during a short-circuit test, and so a photographic technique is best employed; it may also be necessary to increase the circuit-breaker overload settings for the period of the tests. In this case suitable wattmeters must be connected for recording the power input, since the kilowatt-hour meter cannot be utilized. Once again it is advisable to make the necessary current measurements with those meters and instrument transformers which give the highest overall accuracy.

A factor which must also be taken into consideration is the possible saturation of the current transformers when the heavy short-circuit currents are flowing, particularly on the higher voltage tappings. A check on the primary current transformers can be made by metering the currents using the h.v. protection current transformers.

(3.3) Determination of Arc Power

The determination of the arc-power characteristics of a furnace by any direct method is a difficult proposition. The greatest difficulty involved is in the measurement of the true arc voltage, which is essential if an accurate assessment of arc power is to be made. Methods have been tried involving the use of metal probes, water cooled and otherwise, to measure the potential difference across the terminal points of the arc, at the tip of the electrode and the arc spot on the surface of the molten bath, i.e. the so-called anode and cathode spots. However, the position of these spots is continually changing as the arc fluctuates, and the extremely high temperatures attained in the furnace at the root of the arcs makes it impossible to keep the probes
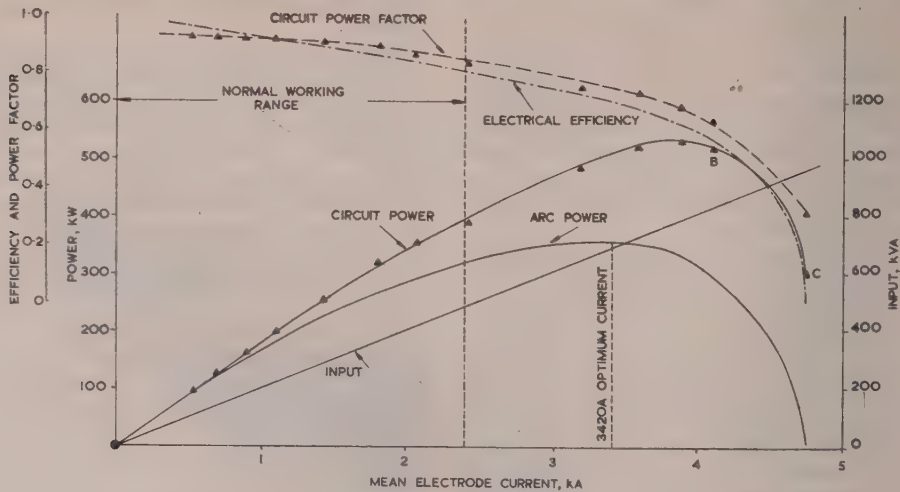
Fig. 2.—Characteristics of the 10 cwt arc furnace on the 110-volt tap.

Supply voltage = 11·3 kV.
Supplementary reactance = 33%.
Total impedance = 56·5%.

inside the furnace for more than a few seconds for any one measurement.

A method has been developed on the 10 cwt experimental furnace for measuring arc voltage using a special probe electrode.[2] One connection is within a few inches of the arcing tip of the electrode and the other is taken to the outside of the steel shell of the furnace. The voltage drop across the molten bath and the furnace lining is found to be negligible, even for short-circuit conditions. With this method the existing furnace wattmeter or supplementary wattmeters can be suitably connected to measure arc power directly, or the power can be calculated from the product of arc voltage and electrode current, since the arc voltage and current are always in phase. However, certain errors are inevitable when measuring arc parameters using conventional voltmeters and ammeters calibrated in r.m.s. values for sinusoidal waveforms.[3]

The procedure used in the determination of arc power is the same as that used in the determination of circuit power, excepting that attention is turned to the observations of arc voltage and power instead of the h.v. instrument readings. In fact, it is often convenient to make the necessary observations for the circuit-power and arc-power characteristics at the same time.

This method for the direct determination of arc power would not be very practicable on a large production furnace, because it necessitates the use of special electrodes. An alternative method which can be used for determining arc power with reasonable accuracy is by measuring the voltage at the electrode clamp (the normal l.v. metering connection) and subtracting from this the voltage drop along the electrode. If it is assumed that this voltage drop is purely resistive, the resistance of the electrode can be obtained by measuring the voltage drop along it during a short-circuit test. The voltage drop for any current is then given by the product of current and resistance.

(3.4) Determination of Power Factor and Electrical Efficiency

The power factor can be determined directly if a power-factor meter is included in the furnace instrumentation. Alternatively, if a reactive-volt-ampere-hour meter is available, average power factor can be calculated from the ratio of reactive kilovolt-ampere-hours to kilowatt-hours used during a given period. If neither of the above instruments is available an approximate

value for the furnace power factor can be obtained by comparing circuit power with total apparent power using existing watt meters, voltmeters and ammeters.

Electrical efficiency, as defined in Section 3, is obtained directly from the ratio of arc power to circuit power.

The electrical characteristics of the 10 cwt furnace on the 110-volt tapping are given in Fig. 2.

(4) EQUIVALENT CIRCUIT FOR THE ARC FURNACE

The complete circuit-power and arc-power curves cannot be determined directly because of the dangers of overloading the furnace transformer in taking the necessary observations. Thus the methods outlined in Sections 3.1–3.4 always leave a part of the power curve to be drawn in without guidance (BC in Fig. 2). The short-circuit current (indicated by the point C) is determined by the total reactance in the furnace circuit—the higher the reactance the lower the short-circuit current and so the greater the portion of the characteristic for which direct observation can be taken. However, an equivalent circuit for the arc furnace can be used to complete the curves with some accuracy, and can even be used to calculate the entire characteristics from a minimum number of observations.

In the electric arc furnace the l.v. busbar system and flexible cables connecting the busbars to the electrode arms carry very heavy currents—up to 40 kA in some installations. It is therefore essential that these conductors should be designed so that the power dissipated in them is a minimum. The inductive reactance of the system must also be taken into consideration, and at such heavy alternating currents both skin effect and proximity effect[4] can be appreciable. It is practically impossible to design a furnace so that the resistance and reactance of the l.v. system can be predicted beforehand, and so it is usually found in practice that each phase has a slightly different resistance and reactance. This has the effect of unbalancing the furnace load with respect to the supply to a degree depending upon the size of the furnace and the relative impedance of the l.v. circuit when compared with that of the transformer windings. Consequently, strictly speaking, the 3-phase arc furnace represents an unbalanced 3-phase star-connected load, and for high accuracy in the calculations of furnace performance it should be treated as such.

Each phase of the 3-phase arc furnace can, for a given voltage tap, be represented approximately by an a.c. series circuit including

(a) A fixed inductive reactance, consisting of the inherent reactance of the furnace transformer, the supplementary reactor and the reactance of the furnace cables and busbars.
(b) A fixed resistance consisting of the transformer windings, cables, busbar resistance and the electrode.
(c) A variable resistance represented by the arc itself.

Consider the equivalent circuit diagram of the furnace as shown in Fig. 3. During a short-circuit test, when the electrodes
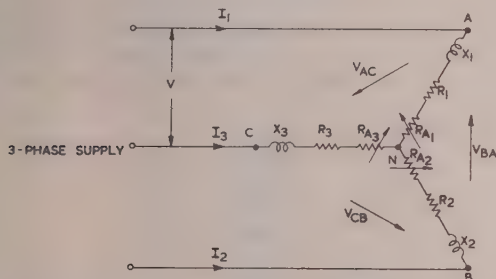

Fig. 3.—Equivalent circuit for the 3-phase arc furnace.

are dipped into a bath of molten metal, the arc resistances will be reduced to zero, so that if suitable instruments are available, the values of the circuit constants, R_1–R_3 and X_1–X_3, can be determined from observations made during the test. The readings required are the three phase voltages measured between A, B and C and the star point, N, respectively, the three phase currents and the power in each phase all measured on the primary side of the furnace transformer.

The above voltage, current and power observations can be made at the same time or separately on each phase if necessary. The furnace constants can then be determined directly from the usual relationships

$$R_n = P_n/I_n^2 \qquad Z_n = V_n/I_n$$

and

$$X_n = \sqrt{(Z_n^2 - R_n^2)}$$

where $n = 1, 2$ and 3.

The resultant values will be the equivalent resistances, reactances and impedances of the furnace circuit referred to the primary windings of the transformer. If the three currents are measured on the secondary side of the furnace transformer, the l.v. phase voltages must be referred to the secondary winding. This can be done with reasonable accuracy by multiplying the voltages by the transformation ratio, k, for the particular voltage tap in use. When the three electrode currents are used the resultant values for the constants will be the equivalent resistances, reactances and impedances referred to the secondary windings.

Once the furnace constants have been calculated, operating points on the circuit-power curve can be readily determined using the formulae developed in the Appendix. The success of this method is entirely dependent on the degree of accuracy attained in the determination of the furnace constants, so that, as discussed in Section 3.2, it is essential that the observations made during the short-circuit tests should be absolutely reliable. Changes in a.c. resistance and the mutual inductance of the flexible cables and busbar system can occur with the heavy currents which flow during short-circuits, so that the furnace constants derived from short-circuit tests may differ from the actual values when operating within the normal current range. This effect, which has been discussed at great length by Markov,[5]

would be difficult to assess in practice and has been ignored in calculations made by the author on furnaces up to 25 tons capacity, without introducing any noticeable errors.

(4.1) Calculation of Operating Points

In most furnace installations the electrode regulator is adjusted to maintain approximately equal currents in the three arcs, but when the electrodes are short-circuited the three currents can be quite unbalanced. For example, in a typical short-circuit test on the 10 cwt furnace the following simultaneous readings were obtained:

Electrode currents	..	..	3 140, 4 560 and 4 300 amp.
Furnace voltage	..	..	20 volts.
Furnace power	..	..	184 kW.

From the equivalent circuit for the 3-phase arc furnace mathematical relationships can be derived between the furnace parameters for the conditions for the three electrode currents to be equal in magnitude [eqns. (13)–(15)]. From these relationships, simple formulae can be obtained for calculating the circuit power for any desired current when the line voltage and the equivalent circuit reactances are known. The circuit power-factor also can be readily determined.

It can be shown that the conditions for maximum circuit power, when the three electrode currents are equal, are that the sum of the circuit resistances shall equal the sum of the circuit reactances, i.e.

$$\Sigma R_n + \Sigma R_{An} = \Sigma X_n \quad . \quad . \quad . \quad . \quad (1)$$

where $n = 1, 2$ and 3.

From this relationship, simple expressions can be derived for maximum circuit power and the corresponding current [eqns. (26) and (27)].

When a series of observations of circuit power and current have been made over the normal working range, the formulae can be used to calculate operating points in order to complete the circuit-power characteristic. Once the circuit-power curve has been drawn, the arc-power characteristic can be deduced by subtracting the total I^2R losses from the input power curve, since the equivalent resistances of the three phases will have been calculated already from the short-circuit tests.

As mentioned earlier, the circuit power-factor can be calculated for any current value, so that the input apparent power can be determined. Electrical efficiency can be obtained directly from the ratio of arc power to circuit power. The best way to illustrate the simplicity of the method for calculating operating points is by a worked example.

Example.—Consider the case of the 10 cwt furnace on the 130-volt tap.

From short-circuit tests the equivalent circuit reactances referred to the secondary windings are $X_1 = 0.0157$ ohm, $X_2 = 0.0113$ ohm and $X_3 = 0.0122$ ohm, so that the total reactance, ΣX_n, is 0.0392 ohm.

The line voltage, V, at the time of tests was 11.9 kV and the transformer turns ratio, k, is $130/11\,000 = 0.0118$; thus the voltage referred to the secondary winding, kV, is 140.7 volts.

For any electrode current, I, to calculate the corresponding circuit power, P_T, the following expressions are used:

$$Z_a = kV/I \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\Sigma R_n' = \sqrt{[3(Z_a)^2 - (\Sigma X_n)^2]} \quad . \quad . \quad . \quad . \quad (3)$$

$$P_T = I^2 \Sigma R_n' \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

For example, if the electrode current is 2·5 kA,

$$Z_a = \frac{140\cdot7}{2500} = 0\cdot0563 \text{ ohm, from eqn. (2),}$$
$$\Sigma R'_n = \sqrt{[3(0\cdot0563)^2 - 0\cdot0392^2]}$$
$$= 0\cdot0893 \text{ ohm from eqn. (3), and}$$
$$P_T = 2500^2 \times 0\cdot0893 \text{ watts}$$
$$= 558 \text{ kW from eqn. (4)}$$

Operating points were calculated on the 130-volt tapping to complete the full circuit-power curve. As a check on the method two points within the normal working range were calculated and compared with direct observations. Power factors were also determined, and the full electrical characteristics on the 130-volt tap are illustrated in Fig. 4. The two calculated points within the working current range fit closely with the observations of

circuit power, and the calculated curve for the circuit-power characteristic is of the shape expected and meets the short-circuit observation in the desired fashion.

From these and other similar results it was considered that the use of an equivalent circuit for the 3-phase arc furnace, and the derived formulae for calculating operating points, was justified and gave results of good accuracy.

(5) ELECTRICAL CHARACTERISTICS OF THE 10 CWT ARC FURNACE

Observations of the power input, the three electrode currents and the power factor were made on the 10 cwt arc furnace over the normal working current range on the six voltage tappings ranging from 88 to 180 volts on open-circuit (the two lowest voltage taps on the furnace are rarely used). It was found that
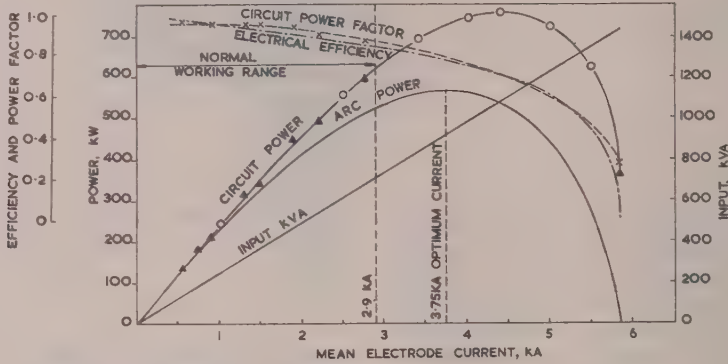

Fig. 4.—Characteristics of the 10 cwt arc furnace on the 130 volt tap.

Supply voltage = 11·9 kV.   x   Observations of power factor.
Supplementary reactance = 22%.   ▲   Observations of circuit power.
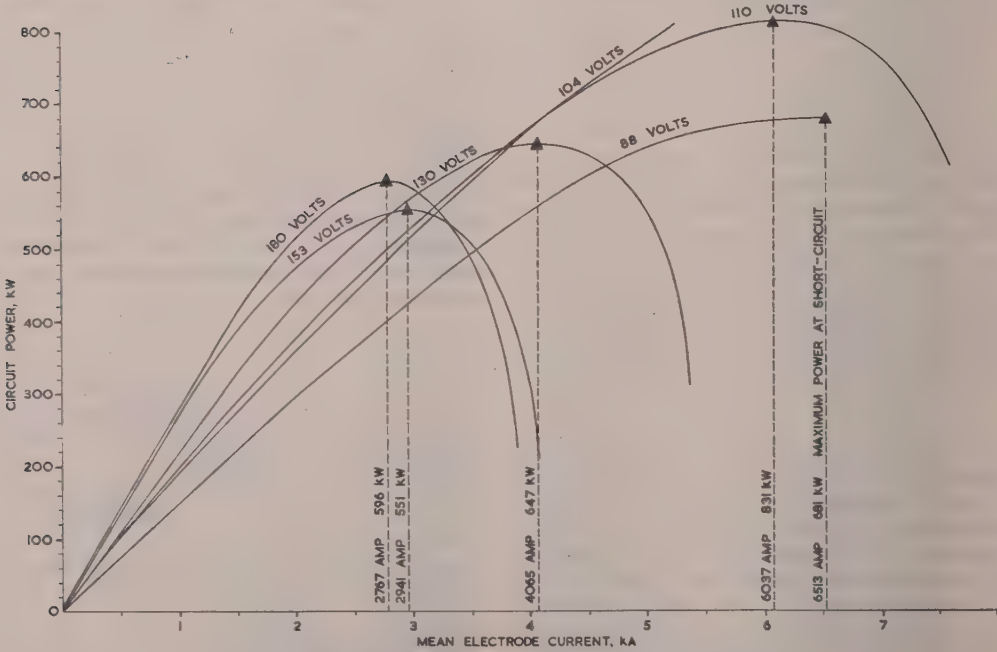Total impedance = 41%.   O   Calculated values.

Fig. 5.—Circuit-power characteristics of the 10 cwt arc furnace.

Supply voltage = 11 kV.
▲ Maximum power levels.

he supply voltage varied considerably over the period of these tests, from 11·0 to 11·9 kV, so that for comparison all the observations were corrected and plotted on the basis of an 11 kV supply.

To complete the circuit-power and power-factor characteristics, short-circuit tests were made and operating points were calculated by the method outlined in Section 4.1; the arc power and electrical efficiency curves were also determined. To compare the performance of the furnace on these six different voltage taps, circuit power is plotted against mean electrode current in Fig. 5. Similarly, the family of arc-power curves are plotted in Fig. 6.

adjusted so that the short-circuit current will not exceed three times the rated full-load secondary current. There is no supplementary reactance in the circuit on the star voltage taps.

A closer analysis of the circuit-power characteristics reveals that, over the normal working range (0–2·6 kA), for a given electrode current the power input increases with furnace voltage. Similarly, an examination of Fig. 6 shows that over the working range the arc power also increases with furnace voltage and the furnace is more efficient, electrically, when operated on the highest voltage tap. The reason is that for a given power input the electrode current is lower at the higher voltages, and if the
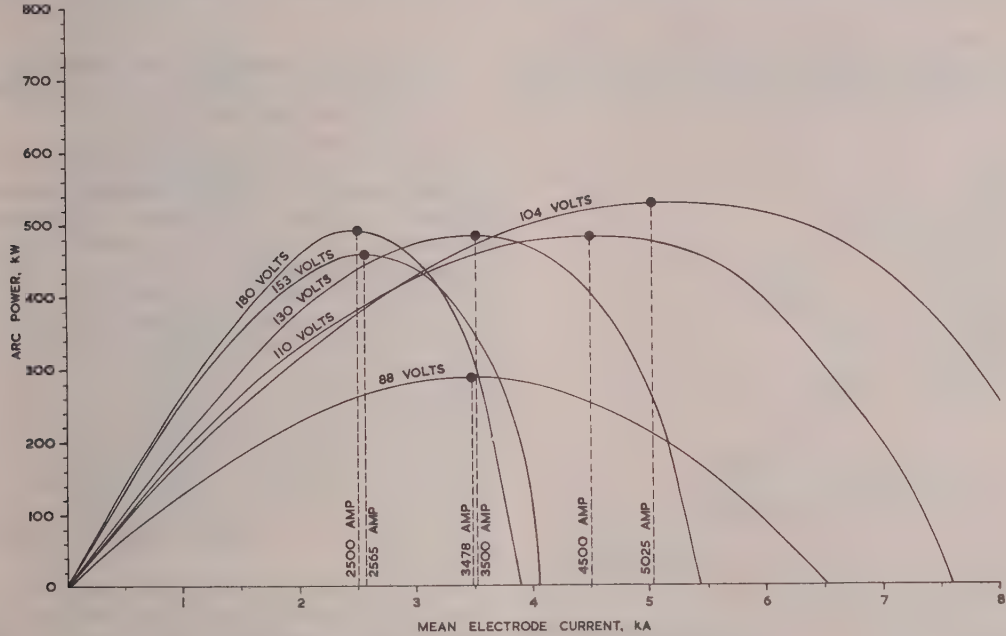

Fig. 6.—Arc-power characteristics of the 10 cwt arc furnace.

Supply voltage = 11 kV.
● Optimum current levels.

From Fig. 5 it appears at first sight that a higher power can be put into the furnace on the four lower voltage taps than on the two highest taps, because of the differences in circuit impedance on the various taps ranging from 31·5% at 104 volts to 50% at 88 volts. Details of the circuit reactance are given in Table 1, where it will be noted that the supplementary reactance in the circuit for the four melting taps (110–180 volts) has been

circuit reactance is correctly adjusted the I^2R losses will be correspondingly decreased.

The optimum current is well above the full-load secondary current on all the voltage taps, so that there is little chance of the optimum level being exceeded during normal operation of the furnace, except when violent current swings occur in the early stages of melting down.

(6) USE OF A CURRENT-LOCUS DIAGRAM

Although the electrical characteristics of a furnace can be determined by the methods previously outlined, the amount of work involved is considerable. Tests similar to those described in Section 3.1 are difficult to perform on production furnaces, owing to the necessary interruption in production entailed in taking series of observations under flat bath conditions, especially if high power inputs are to be measured. Multiple short-circuit tests, required to determine phase voltages and power per phase, are also detrimental to the steel-making process.

A simplified method can be used to calculate furnace characteristics by treating the furnace as a balanced 3-phase load, and from tests made on the 10 cwt furnace and on production furnaces this method has been shown to be accurate enough for all practical purposes.

Table 1

DETAILS OF CIRCUIT REACTANCE FOR 11 kV 500 kVA ARC FURNACE

Voltage tap	Full-load secondary current	Supplementary reactance	Impedance at full-load apparent power	Short-circuit current / Full-load current
volts	amp	%	%	%
180	1 605	33	41·5	240
153	1 890	33	46·5	215
130	2 225	22	41	245
110	2 620	11	35	285
104	1 605	Zero	31·5	320*
88	1 890	Zero	50	200*

* At full-load secondary apparent power.

To use the simplified method the furnace must be equipped with an h.v. line voltmeter, an ammeter for each of the three phases and a double-element indicating wattmeter or a power-factor meter. These instruments are required so that the supply voltage, mean current per phase and input power can be determined during a short-circuit test when the three electrodes are dipped simultaneously into a molten-steel bath. From these observations, input apparent power and short-circuit power factor can be calculated. Only one short-circuit test is required for each voltage tap, and the observations obtained during the test are used to construct a current-locus diagram which represents the variable furnace load for that particular voltage tapping.

If the arc-furnace circuit is considered as being a simple a.c. series circuit of constant input voltage, constant inductive reactance and variable resistance, it is well known that for such a circuit the locus of all possible current vectors lies on a semi-
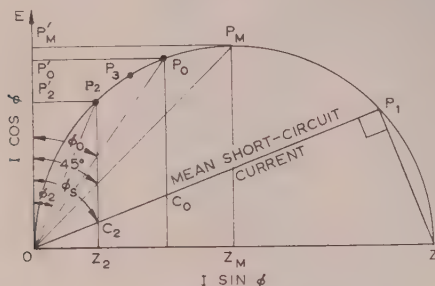

Fig. 7.—Current-locus diagram.

circle as shown in Fig. 7. The semicircular locus is located as follows.

Draw the short-circuit current vector OP_1 at an angle ϕ_s to the vertical voltage vector OE (where ϕ_s is the phase angle on short-circuit).

Draw P_1Z at right angles to OP_1. The required semicircle can then be drawn with OZ as its diameter, where OZ is perpendicular to OE.

All operating points P_2, P_3, etc., then lie on the semicircle. Circuit power, arc power, electrical efficiency, power factor and apparent power can be obtained directly from the diagram, e.g. for the current OP_2, power factor $= \cos \phi_2$. $I \cos \phi_2 = OP_2'$.

Then the active power input is $\sqrt{3} \cdot OE \cdot OP_2'$ and the apparent power input is $\sqrt{3} \cdot OE \cdot OP_2$.

Draw P_2Z_2 perpendicular to OZ and let C_2 be the intercept in OP_1; arc power is then given by $\sqrt{3} \cdot OE \cdot P_2C_2$ and electrical efficiency by

$$\frac{P_2C_2}{P_2Z_2} = \frac{C_2P_2}{OP_2'}$$

Draw current vector OP_M at 45° to OE; then the maximum circuit power is $\sqrt{3} \cdot OE \cdot OP_M'$. Draw OP_0 at angle $\phi_0 = \frac{1}{2}\phi_s$ to OE; then the optimum current is OP_0, and the maximum arc power is $\sqrt{3} \cdot OE \cdot P_0C_0$; then the circuit power corresponding to the maximum arc power is $\sqrt{3} \cdot OE \cdot OP_0'$.

Current-locus diagrams were drawn from short-circuit test results on the 10 cwt furnace, and from these diagrams the furnace characteristics were determined for three of the voltage taps previously investigated.

The curves produced were compared with those previously obtained by direct observation and calculation, and it was found that for both the circuit-power and arc-power characteristics there was little difference in the results obtained by the two

methods. For example, for the 130-volt tap the circuit power for an electrode current of 2·5 kA was determined from the locus diagram as 554 kW, which compares closely with the calculated value of 558 kW given in Section 4.1.

The optimum currents determined by the two methods were also found to be similar; e.g. for the 130-volt tap the optimum current was given by the locus diagram as 3 685 amp, compared with the 3 750 amp previously established (see Fig. 4). Since the rated full-load secondary current on this voltage tap is only 2 225 amp, there is no danger of the optimum level being exceeded during normal operation of the furnace, so that the slight error introduced by using the simple 3-phase treatment is not critical.

(7) COMPARISON BETWEEN THE METHODS AVAILABLE FOR THE DETERMINATION OF ARC-FURNACE ELECTRICAL CHARACTERISTICS

The direct method for the determination of furnace performance curves has limited application because of the difficulties involved in making a prolonged series of tests on a production furnace. For an accurate completion of the circuit-power curve observations over an extended current range are required preferably beyond the current corresponding to maximum circuit power, and this means that the circuit reactance must be high.

If a series of short-circuit tests can be made to determine the furnace constants, without interfering too much with production, the complete furnace characteristic can be derived by calculation using simple formulae obtained from an analysis of the furnace equivalent circuit. The accuracy of this method can easily be checked by comparing calculated results with observations within the normal working range and noting how the resulting circuit power curve matches up with the observed short-circuit point. The success of this method is, of course, entirely dependent on the accuracy of the measurements taken during the short-circuit tests.

Performance curves can be drawn reasonably accurately by using a current-locus diagram plotted from data obtained during a single short-circuit test. When the working current range is well below the optimum level, this simple technique gives results in close agreement with those obtained by the two other methods.

(8) CONCLUSIONS

Experimental work on a 10 cwt furnace has shown that the electrical characteristics of an arc furnace can be determined by calculation. To compare operation on different voltage tappings, the furnace curves can be plotted using locus diagrams derived from results obtained during short-circuit tests. This method is sufficiently accurate when the working current is below the optimum level.

If the circuit reactance is high the load current can approach or exceed the optimum value, and it is important that the optimum currents should be forecast accurately so that the load does not exceed these values during normal operation of the furnace, thereby wasting power.

The characteristic curves for the 10 cwt furnace show that it is most efficient, electrically, when operated on the highest voltage tap.

(10) REFERENCES

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(11) APPENDIX

Determination of Maximum Power in the Arc Furnace and the Calculation of Operating Points when the Three Electrode Currents are Equal

Consider the equivalent circuit for the 3-phase arc furnace as shown in Fig. 3.

Using the symbolic method and taking V_{BA} as reference vector,

$$V_{BA} = V + j0 \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$V_{AC} = -\frac{V}{2} + j\frac{\sqrt{3}}{2}V \quad . \quad . \quad . \quad . \quad (6)$$

$$V_{CB} = -\frac{V}{2} - j\frac{\sqrt{3}}{2}V \quad . \quad . \quad . \quad . \quad (7)$$

Applying Kirchhoff's laws we have

$$I_1 + I_2 + I_3 = 0 \quad . \quad . \quad . \quad . \quad . \quad (8)$$

For the circuit ANB,

$$V_{BA} = I_2(R_2' + jX_2) - I_1(R_1' + jX_1) = I_2Z_2' - I_1Z_1' \quad . \quad (9)$$

Similar symmetrical equations may be written for circuits ANC and BNC.

Solving for I_1, we arrive at the expression

$$I_1 = \frac{Z_3'V_{AB} + Z_2'V_{AC}}{\Sigma(Z_1'Z_2')} \quad . \quad . \quad . \quad . \quad (10)$$

or

$$I_1 = \frac{VZ_{a1}}{\Sigma(Z_1'Z_2')} \quad . \quad . \quad . \quad . \quad (11)$$

where $\quad \Sigma(Z_1'Z_2') = Z_1'Z_2' + Z_2'Z_3' + Z_3'Z_1'$

Similar symmetrical expressions can be written for I_2 and I_3. For the magnitudes of the three currents to be equal, $I_1 = I_2 = I_3 = I$, i.e. $Z_{a1} = Z_{a2} = Z_{a3} = Z_a$ since

$$I_n = \left| \frac{VZ_{an}}{\Sigma(Z_1'Z_2')} \right| = \frac{V}{|\Sigma(Z_1'Z_2')|} Z_{an} \text{ for } n = 1, 2 \text{ or } 3.$$

Substituting in eqn. (11) using eqns. (5) and (6) gives

$$Z_{a1} = \left(-\frac{R_2'}{2} - \frac{\sqrt{3}}{2}X_2 - R_3'\right) - j\left(\frac{\sqrt{3}}{2}R_2' - \frac{X_2}{2} - X_3\right)$$

Therefore

$$Z_{a1}^2 = R_2'^2 + R_3'^2 + X_2^2 + X_3^2 + R_2'R_3' + X_2X_3$$
$$+ \sqrt{3}(X_2R_3' - X_3R_2') \quad . \quad (12)$$

By symmetry, similar expressions can be obtained for Z_{a2}^2 and Z_{a3}^2.

Now it can be verified that the general conditions for $Z_{a1}^2 = Z_{a2}^2 = Z_{a3}^2$ are that, simultaneously,

$$\sqrt{3}(X_1 - X_3) = R_1' - 2R_2' + R_3' \quad . \quad . \quad . \quad (13)$$

$$\sqrt{3}(X_2 - X_1) = R_2' - 2R_3' + R_1' \quad . \quad . \quad . \quad (14)$$

$$\sqrt{3}(X_3 - X_2) = R_3' - 2R_1' + R_2' \quad . \quad . \quad . \quad (15)$$

Let $R_1' + R_2' + R_3' = 3R$; then from eqns. (13)–(15),

$$R_1' = R + \frac{1}{\sqrt{3}}(X_2 - X_3) \quad . \quad . \quad . \quad . \quad (16)$$

and similar expressions can be written for R_2' and R_3'. Substituting in eqn. (12) gives

$$Z_{a1}^2 = \left[R + \frac{1}{\sqrt{3}}(X_3 - X_1)\right]^2 + \left[R + \frac{1}{\sqrt{3}}(X_1 - X_2)\right]^2$$
$$+ \left[R + \frac{1}{\sqrt{3}}(X_3 - X_1)\right] \cdot \left[R + \frac{1}{\sqrt{3}}(X_1 - X_2)\right]$$
$$+ X_2^2 + X_3^2 + X_2X_3 + \sqrt{3}\left\{\left[R + \frac{1}{\sqrt{3}}(X_1 - X_2)\right]X_2 \right.$$
$$\left. - \left[R + \frac{1}{\sqrt{3}}(X_3 - X_1)\right]X_3\right\}$$

when $\qquad\qquad Z_{a1}^2 = Z_{a2}^2 = Z_{a3}^2 = Z_a^2$

i.e. $\quad Z_a^2 = 3R^2 + \frac{1}{3}[\Sigma X_n^2 + 2\Sigma(X_1X_2)]$ for $n = 1, 2$ and 3
$$= 3R^2 + \frac{1}{3}(\Sigma X_n)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

Let $\Sigma X_n = 3X$; then

$$Z_a^2 = 3(R^2 + X^2) \quad . \quad . \quad . \quad . \quad (18)$$

Now the total power is

$$P_T = I_1^2 R_1' + I_2^2 R_2' + I_3^2 R_3'$$

and when $I_1 = I_2 = I_3 = I$,

$$P_T = I^2 \Sigma R_n' = 3I^2 R$$

$$= \frac{3V^2 Z_a^2 R}{|\Sigma(Z_1'Z_2')|^2} \quad . \quad . \quad . \quad . \quad (19)$$

$$Z_1'Z_2' = R_1'R_2' - X_1X_2 + j(R_1'X_2 + R_2'X_1)$$

Therefore

$$\Sigma(Z_1'Z_2') = \Sigma(R_1'R_2') - \Sigma(X_1X_2) + j\Sigma(R_1'X_2) \text{ for } n = 1, 2 \text{ and } 3,$$

i.e. $|\Sigma(Z_1'Z_2')|^2 = [\Sigma(R_1'R_2') - \Sigma(X_1X_2)]^2 + [\Sigma(R_1'X_2)]^2$. (20)

Now $\qquad \Sigma(R_1'R_2') = 3R^2 - \frac{1}{3}\Sigma X_n^2 + \frac{1}{3}\Sigma(X_1X_2)$ . . (21)

for $n = 1, 2$ and 3.
Also it can be shown that

$$\Sigma(R_1'X_2) = 2R\Sigma X_n = 6RX \quad . \quad . \quad . \quad (22)$$

Substituting in eqn. (20) gives

$$|\Sigma(Z_1'Z_2')|^2 = (3R^2 + 3X^2)^2 = 9(R^2 + X^2)^2 \quad . \quad (23)$$

Using eqns. (18) and (23) in eqn. (19):

$$P_T = \frac{9V^2 R(R^2 + X^2)}{9(R^2 + X^2)^2} = \frac{V^2 R}{R^2 + X^2} \cdot \quad . \quad . \quad (24)$$

also
$$I = \frac{V}{\sqrt{[3(R^2 + X^2)]}} = \frac{V}{Z_a} \quad \cdots \cdots \quad (25)$$

The values of X_1, X_2 and X_3 are fixed in practice, so that $X = \Sigma X_n/3 = $ a constant.

Differentiating eqn. (24) with respect to R gives

$$\frac{dP_T}{dR} = \frac{V^2}{(R^2 + X^2)^2}(X^2 - R^2) = 0 \text{ when } R = \pm X;$$

i.e. for a maximum or minimum.

Since $R = \Sigma R_n'/3$ is always positive, and from inspection of eqn. (24), P_T is a maximum when $R = X$, i.e. when $\Sigma R_n' = \Sigma X_n$.

Therefore, for maximum circuit power when the three electrode currents are equal* the sum of the resistances, including the three arcs, must be equal to the sum of the reactances in the furnace circuit.

From eqn. (24),

$$P_{T max} = \frac{V^2}{2X} = \frac{3V^2}{2\Sigma X_n} \quad \cdots \cdots \quad (26)$$

From eqn. (25),

$$I_{max} = \frac{V}{\sqrt{(6X^2)}} = \sqrt{\frac{3}{2}} \frac{V}{\Sigma X_n} = \frac{1 \cdot 225 V}{\Sigma X_n} \quad \cdots \quad (27)$$

and from eqn. (19),

$$P_{T max} = I_{max}^2 \Sigma X_n \quad \cdots \cdots \cdots \quad (28)$$

* Note.—The general condition for P_T to be a maximum when $I_1 \neq I_2 \neq I_3$ is that $R_n' = X_n$ for $n = 1, 2$ and 3.

In the general unbalanced 3-phase circuit power-factor is given by

$$\frac{I_1^2 R_1' + I_2^2 R_2' + I_3^2 R_3'}{V_1 I_1 + V_2 I_2 + V_3 I_3} = \frac{\Sigma(I_n^2 R_n')}{\Sigma(I_n^2 Z_n')} \quad \cdots \quad (29)$$

Therefore
$$\text{power factor} = \frac{\Sigma R_n'}{\Sigma Z_n'} \quad \cdots \cdots \quad (30)$$

when $I_1 = I_2 = I_3 = I$.

From the above mathematical relationships, operating points on the circuit-power and power-factor curves can readily be determined when the three currents are equal if the line voltage, V, and the reactances, X_1, X_2 and X_3, are known, since from eqn. (25) $Z_a = V/I$ and from eqn. (17) $3Z_a^2 = (\Sigma R_n')^2 + (\Sigma X_n)^2$.

Therefore
$$\Sigma R_n' = \sqrt{[3Z_a^2 - (\Sigma X_n)^2]} \quad \cdots \cdots \quad (31)$$
$$n = 1, 2 \text{ and } 3.$$

Moreover, from eqns. (18) and (24),

$$P_T = \frac{3RV^2}{Z_a^2} = \frac{V^2 \Sigma R_n'}{Z_a^2} \quad \cdots \cdots \quad (32)$$

Thus for any given value of I, Z_a and $\Sigma R_n'$ can easily be calculated from eqns. (25) and (31) and the circuit power can be obtained by direct substitution in eqns. (19) or (32).

R_1', R_2' and R_3' can be determined from eqn. (16), etc., and Z_n' can be calculated from the usual relationship $Z_n' = \sqrt{(R_n'^2 + X_n^2)}$ for $n = 1, 2$ and 3, when the circuit power-factor is obtained by direct substitution in eqn. (30).

DISCUSSION ON THE ABOVE PAPER

Before the UTILIZATION SECTION 8*th December, the* MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL 5*th December, and the* SHEFFIELD SUB-CENTRE *at* SHEFFIELD 14*th December,* 1960.

Mr. J. R. Phillips (*at London*): The first arc furnaces in which I was interested (about 1936) had been built during the 1914–18 War. Their busbar systems had not been designed to keep the reactance down and I was able to make modifications which considerably improved their performance. This encouraged me to make tests on newer furnaces, and I found it possible to reduce the added reactance on all but the highest voltage tapping and to advise the operators regarding the maximum current which could be used economically on each voltage. These changes made savings in current and electrode consumption. I was therefore interested when the author joined B.I.S.R.A. with a view to encouraging the better design and operation of arc furnaces.

The tests reported in the paper were carried out on a 10 cwt furnace in which the relative furnace reactance and transformer size were unusual. The family of curves produced was not representative of a large production furnace, and I should have liked the author to show a more normal set of curves.

Those wishing to make short-circuit tests would be advised to start on the lower voltages and to take care about the uniform dipping of the three electrodes. The choice of suitable current transformers and instruments to work at the higher than normal current and low power factor is also important. I have found that high-speed pen-recording instruments have many advantages, since the shape of the recordings show whether a good test has been made.

Referring to Section 4, I think the point is that, owing to its physical shape, a conventional arc furnace has been treated as three single-phase supplies feeding the three electrodes. This has resulted in an uneven balance of power and high reactance, and the problem worsens as the size of furnace increases.

Recently improved designs have been made in several countries in which the delta connection has been transferred from the top of the transformer to the furnace itself. In this way the overall reactance is reduced and the power supply to the three arcs made more uniform.

In the small B.I.S.R.A. furnace the optimum current is less than the transformer rating on each voltage. On a production furnace it is possible to exceed the optimum current on the lower voltages, resulting in a waste of power and electrodes. All furnace controllers should be designed so that the optimum current cannot be exceeded on any voltage tapping.

The author has approached these tests in three different ways and shown that the circle diagram can be applied. For an existing furnace the circle diagram can be defined by means of a short-circuit test, and for a new furnace I suggest that the short-circuit current and power factor at the time of short-circuit should be specified.

As an electrical engineer one tends to concentrate on reducing electrical losses, but it must be pointed out that the thermal losses can be more important. During the early stages of a melt a high voltage, with lower current and high electrical efficiency can be justified, since most of the heat from the long arc is absorbed by the cold charge. When the charge is molten, a long arc would result in excessive heat loss to the refractories and a lower voltage will result in higher overall efficiency.

Large arc furnaces are of concern to supply engineers because of the voltage flicker they cause on the system. I should like the author's opinion on the best choice of reactance and other features to minimize this problem.

Mr. P. R. Harrison (*at London*): In general, I consider that only the equivalent-circuit theory is of use in design. There are

however, many variations which can occur, particularly the changes of reactance which occur when the in-line position of the arms changes. Recent measurements show that these variations are important and can be up to 20% of the arm reactance.

It is thus possible to obtain a series of equivalent circuits, and designers must be very careful to select appropriate values in making forecasts of the furnace characteristics.

The accuracy of measurement is very important: many people tend to use ordinary switchboard instruments and to read averages during the dip test. But the parameters can vary considerably beyond those calculated by these methods, and some very misleading curves can be plotted unless the proper instruments are used. I endorse the proposed use of the recording instrument, but one should have a whole set of special instruments to obtain the design characteristics. When the furnace characteristics are plotted from averages they show 3-phase readings on the circle diagram, and one usually finds that the power factor curve, for example, is optimistic. As an average it may be 10% optimistic, and this seems to be due to the difference between the three electrodes, the out-of-balance reactance, the effect of the phase rotation, and the square waveshape which occurs on arc furnaces. Therefore, although the theory does seem to apply generally, and accepting that the furnace at B.I.S.R.A. is a rather peculiar one and gives somewhat different results from the production furnace, it must be very carefully applied to prevent misleading results.

Mr. H. J. Sheppard (*at London*): An engineer who is concerned with the provision of electricity supply to an arc furnace is interested mainly in its performance on the highest transformer tapping, which is generally used during the melting-down period. More details of the characteristics of the author's furnace on the 180-volt tap would therefore be welcome.

Table 1 gives for this tap the impedance at full-load apparent power as 41·5%, with 33% supplementary reactance. This would seem to imply that the impedance of the furnace transformer plus connections and electrodes is only 8·5%. Is this correct?

The problems of supplying the largest arc furnaces now under construction are necessitating their direct connection to the 132 or 275 kV Grid in order to obtain a system impedance low enough to keep voltage fluctuations below seriously noticeable levels. In order to reduce the high costs which this entails, it is important that the fluctuating characteristics of the arc-furnace load should be improved, and I hope that a future paper will be able to record progress in this direction.

Mr. W. J. Kelsey (*at London*): The paper brings out the necessity of determining the characteristics of arc furnaces before they are built. This is not an easy job, particularly when dealing with larger units. We have been doing considerable work on this problem and find that, so long as the system reactance is known back to the infinite busbars, certain very useful characteristics can be derived; we appreciate that these are not perfect, bearing in mind the load variations which occur during the breaking-in period. However, to prepare a design, certain assumptions must be made and the characteristics, whether calculated or measured, are based on steady-state conditions.

With respect to the reactance of the arc furnace, it is most important and great care must be taken in the design of the l.v. system. Of even greater importance is the arrangement of the flexible leads. Not only does this help to reduce reactance, but it can have a twofold effect on side-wall wear and erosion of the furnace lining.

With regard to voltage flicker, it would appear that, to design an arc furnace to work under reasonably efficient conditions, it will not be possible to meet the present requirements of the supply authorities without corrective devices such as buffer reactors and synchronous capacitors, which are expensive. The study of a number of installations showed that to meet these requirements, for example, on a 10 MVA installation, assuming a 2-phase short-circuit, involved the inclusion of 30% buffer reactance and a 15 MVAr synchronous capacitor.

Mr. W. L. Harrison (*at London*): The paper deals with the method of calculation which is essential to the electrical engineer designing the arc furnace, and is certainly of interest to those contemplating the installation of larger and higher-powered furnaces. The choice of arc voltages and operating currents for a given size and power rating of furnace has a great bearing on its possible performance. The use of electricity for melting metals demands a thorough investigation of the economics, and inevitably one must consider an arc-furnace design which will work at the highest possible power factor and electrical efficiency, and will melt steel with a minimum energy consumption. Performance characteristics can differ from calculated values and may be on occasions very disappointing; it is therefore necessary to consider the overall design of the furnace, which includes the method of electrode control and the strength of the associated mechanical system employed to carry the electrodes and their repositioning within the furnace.

The Von Roll connection, which is a method of fully interleaving the heavy-current connections from the transformer to make the delta connection at the electrode clamps, results in balanced electrode currents, a low-reactance furnace circuit and therefore a high power factor, thus minimizing the reactive-power swing of the electrode; it leads to even wearing of the refractory lining and therefore greater output from the furnace. Furnaces employing this connection are working on the Continent, and a number of 150-ton 40 MVA units are now under construction for installation in Britain. In Switzerland there is a 40-ton 18 MVA installation employing high-speed hydraulic electrode regulation with the Von Roll balanced-current electrode connection; its average working power factor during the breakdown period is 0·91–0·92, which is much higher than anything yet attained in Britain.

Mr. T. W. E. Blazey (*at Liverpool*): The paper deals specifically with tests carried out on a direct-arc type of furnace. Could the author confirm whether the determination of such electrical characteristics relates to this type of furnace only, or can they also be applied as successfully to the indirect-arc type?.

Has the author carried out comparative tests on other furnaces to prove the current-locus method? He claims an accuracy better than 1% with the calculated method. Can he give further data to support the current-locus method and indicate the degree of accuracy one could expect?

Figs. 2, 4 and 6 and Table 1 indicate that the normal working range at any of the taps is well below the maximum arc power which could be achieved, and that the rated transformer secondary currents are below those desired for electrode currents for maximum arc power at any tap. The author mentions the danger of instability at or near to the point of maximum arc power, but is there not some justification for a transformer rating to suit the characteristics of the furnace, so that working can be maintained closer to maximum arc power? Commercial considerations usually demand maximum power from production plants, even at slightly reduced efficiencies. Power-factor-correction equipment on the l.v. side could be an advantage in obtaining better power factor and possible efficiencies.

Mr. J. E. Macfarlane (*at Liverpool, communicated*): The simplicity of these determinations is refreshing and shows how simple theory can have an application in practice.

Can the author state how the voltage of the arc is divided at the electrodes, arc and melt? With a mercury-arc rectifier the

otal voltage drop is about 25 volts at the anode, cathode and arc.

It would add to the usefulness of Fig. 7 if a power-factor quadrant were drawn (as shown in Fig. A) so that the power
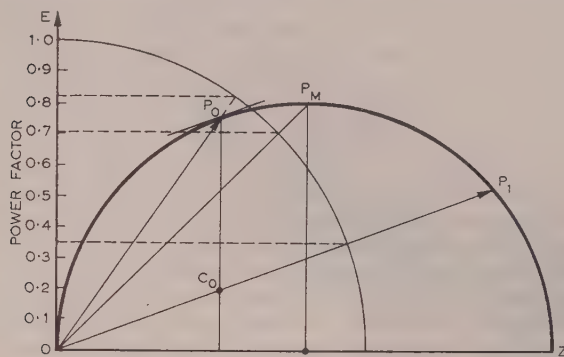

Fig. A.—Power-factor quadrant added to Fig. 7.

factor could be read off directly instead of by means of angles.

The mean short-circuit current vector OP_1 could also be called an 'output line', since all ordinates to the circle above this line are a measure of the power output. The point P_0 is also located by a tangent to the circle parallel to OP_1, and C_0P_0 is the maximum ordinate to the circle.

Mr. R. D. Langman (*at Sheffield*): Little has been said about the detailed use which may be made of the steady-state characteristics of an arc furnace determined by the methods mentioned in the paper. It would appear that the most direct use is associated with determining the best operational current for a given furnace transformer tap and in deciding what additional reactance, if any, is required. The essential point to note is that for a given transformer tap the author and previous contributors have inferred arc-current control. The majority of arc furnaces today are fitted with what is known as 'arc impedance' control, which, if physically realizable, is certainly not synonymous with arc-current control. It is interesting to note that the first automatic arc-furnace regulators were current controllers and that because of voltage protection requirements these early devices developed naturally into impedance control. This is achieved in practice by closed-loop control of the error equation

$$\epsilon_1 = K_1 V_{arc} - K_2 I_{arc}$$

where K_1 and K_2 are constants.

Unfortunately, arc voltage is difficult to measure. The latest improvements to this form of control have provided a means whereby busbar voltage is used and compensation for the impedance drop between this measurement and the arc is made.

Would the author comment on the use of the static characteristics in determining a suitable criterion for arc-furnace control? Are we, in fact, suggesting a return to the early days of arc-current control?

Mr. F. L. Parkin (*at Sheffield*): the author has proved that the arc furnace can be treated as a balanced 3-phase star-connected load for the purpose of determining the characteristics. The figures are sufficiently accurate for a small furnace, but there may be some doubt whether the method is good enough for a really large furnace.

I should therefore like to develop this theme, and consider for a moment the fundamental reasons for unbalanced conditions (apart from the peculiarities of the arc itself and the wandering of the star point). They are due to (a)' lower resistance and self-inductance of the centre phase, owing to the

shorter run of busbars, (b) the effect of mutual inductance of three sets of busbars and flexible leads arranged in line, and (c) magnetic effect and the theory that the mass of metal in the electrode mast causes some measure of inductive out-of-balance. By far the most important is cause (b), and many useful data are now available.*

In the latter, a study of a typical 70-ton 20 MVA furnace showed that the near electrode carried 10% excess power, and of the two electrodes farther from the transformer, the 'cold phase' carried 10% less than mean power compared with the so-called 'hot phase', which carried the mean arc power (3·3 MW per electrode). Reversing the phase rotation causes the location of the far-side hot and cold electrodes to be interchanged, but in all cases the near electrode retains the greatest arc power unless some compensation device is adopted.

The result is two hot spots or patches in the furnace lining and, in broad terms, the larger the furnace the more important this becomes, particularly with quick-melting furnaces which rely upon 95% availability and minimum time for repairs or patching. From theoretical considerations, each electrode regulator should have a different current setting.

Dr. E. Friedlander (*at Sheffield*): We have given some consideration to the problem of voltage flicker. An attempt to check sudden changes of current by a fast automatic correction which operated within 3 cycles of the a.c. frequency proved to be insufficient. A further investigation revealed that, almost independently of the frequency, any sudden disturbance which is not corrected within less than 5–10 millisec is clearly visible. A correction within 60 millisec therefore cannot be good enough. It will actually duplicate the number of disturbances, since not only the initial step, but also its correction, becomes independently visible. Other methods of correction are under investigation. Laboratory experiments are so far promising, but it is obvious that the problem will not be solved by inexpensive remedies unless this can be done at the root of the furnace operation itself.

The author shows an oscillogram which draws attention to the important influence of the series reactance in controlling the duration of the zero passage of the current and with it the tendency of the starting-up arc to be temporarily extinguished. This is likely to be due to the low voltage available at the instant of the zero passage of the current if the power factor is high. An arc stabilized only by a series resistance without reactance could not possibly operate without a long zero-current period, because re-ignition in each half-cycle must wait until the applied voltage is at least as great as the arc voltage required. The trend of modern arc furnaces to have low reactances must consequently be detrimental from the aspect of voltage flicker. On the other hand, any attempt to equalise current consumption in the interest of reduced voltage flicker would seem to involve the use of large equipment to compensate for the unavoidable reactive-power consumption. Would it not be preferable as a first step to reduce the short-circuit currents by large reactors and rather to compensate for the increased reactive power by the installation of static capacitors?

Mr. J. Ravenscroft (*in reply*): I agree with Mr. Phillips that the characteristics of the 10 cwt furnace are not representative of a large production furnace because of the unusual relationship of the reactance of the furnace transformer and the supplementary reactor when compared with the reactance of the furnace l.v. circuit. A more typical set of performance curves for a production furnace is shown in Fig. B; these are for a 15–18 ton capacity furnace with a 4·5 MVA transformer, and they show that

* Schwabe, W. E.: 'Utilization of Power in Electric Arc Furnaces', *Carbon and Graphite News*, November, 1958, 5, No. 2.
Brosovic, J. A.: 'Arc-Furnace Analysis via Photography', *Iron and Steel Engineer*, November, 1959, 36, No. 11, p. 85.
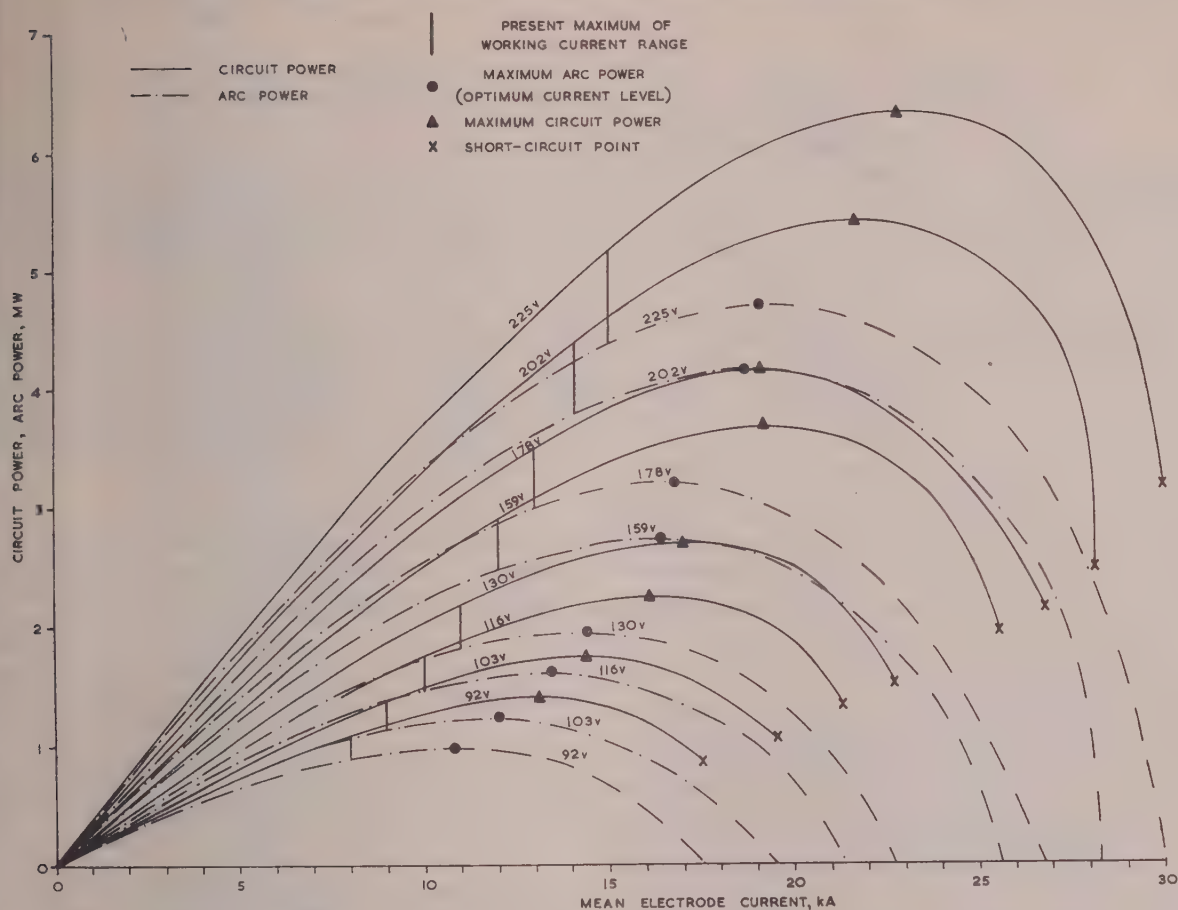
Fig. B.—Electrical characteristics of a 15–18-ton capacity arc furnace.

the optimum current decreases from about 19 kA on the 225-volt tap to 11 kA on the 92-volt tap, which illustrates the importance of reducing the maximum working currents on the lower-voltage taps.

In answer to Mr. Sheppard, the impedance figures given for the 180-volt tap are correct, although it should be stressed that the impedances given in Table 1 are only mean values for the three phases, since the impedances of the l.v. connections of the furnace are grossly unbalanced. Further details of the electrical characteristics of the B.I.S.R.A. furnace on the 180-volt tap have been published elsewhere.*

In reply to Mr. Blazey, the methods outlined in the paper have been used to determine the electrical characteristics of 3-phase direct-arc furnaces with capacities ranging from 3 to 70 tons. In all cases comparisons of the current-locus method with the more elaborate techniques for the determination of furnace curves have shown agreement within 1 % over the working current range. A typical comparison of the curves obtained by using a current-locus diagram with those determined by calculation is shown in Fig. C.

I do not see any reason why the principles outlined in the paper should not be applied for the determination of the characteristics of indirect-arc furnaces, although in this type, where heat is normally transferred to the charge by radiation and convection from a single arc between two electrodes, a short-

* RAVENSCROFT, J., and COPLEY, D. B.: 'The Effect of Circuit Reactance on Arc Furnace Performance', *Proceedings of the B.I.S.R.A. 51st Steelmaking Conference*, September, 1958, p. 17.

circuit test would have to be made by striking the electrodes together.

I do not agree with Mr. Blazey's suggestion that the arc-furnace transformer should be designed so that the furnace can be worked at or near the optimum current level; in fact, I should say that the converse was true. The term 'optimum current' is rather a misnomer, since it is not the best operating current but the value which should never be exceeded. In practice, if a furnace has to be worked at or near the optimum current level to achieve rated apparent power, this means that there is too much reactance in the furnace circuit. In a well-designed low-reactance furnace the full-load current would be well below the optimum value, and this would give a high working power factor and electrical efficiency.

Mr. Langman is confusing the function of the automatic electrode-position control with that of the normal requirement of the furnace operator to select his working power levels. The furnace curves indicate the best working currents for each voltage tapping and can be used to advise the melter in his selection of voltage and current combinations for each stage of the metallurgical process. The automatic electrode regulator attempts to control the power in the arcs at a value corresponding to these preset current and voltage settings, and its main purpose is to correct the short-term disturbances in the arcs caused by the movement of the charge during melting and the variations due to changes in the slag-covering of the melt and furnace atmosphere during refining. Accordingly, I cannot see how the static
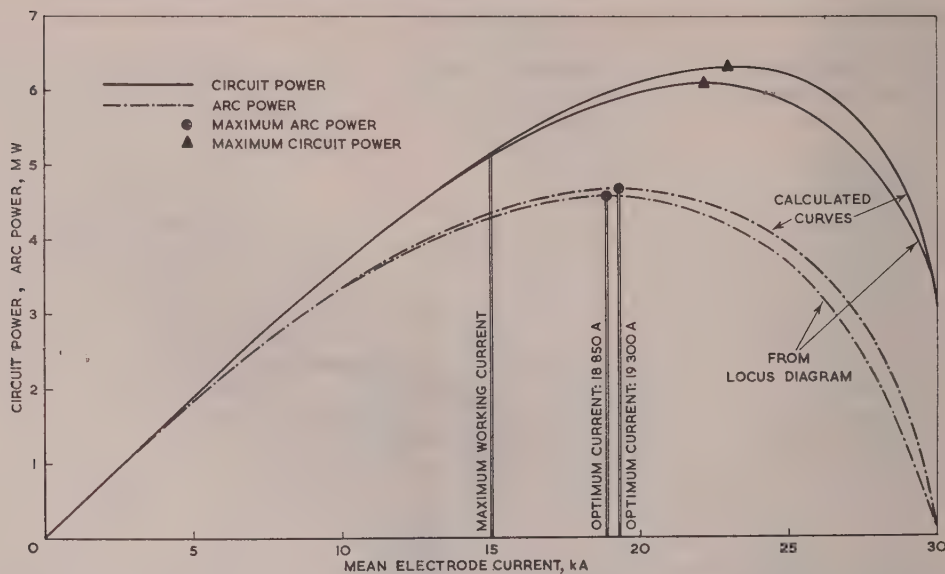
Fig. C.—Comparison of furnace power curves determined by calculation and from current-locus diagram.

characteristics of the furnace can be used to establish criteria for electrode regulation.

In answer to Mr. Macfarlane, the division of the voltage drops in the arc depends to a large extent on arc length. For arcs a few inches long most of the voltage drop occurs in the arc column, which has a virtually constant potential gradient of about 12 volts/cm; there is a drop of some 20–40 volts in the anode and cathode regions. For very short arcs the arc voltage is almost entirely at the electrodes and is relatively independent of current changes.*

Messrs. Phillips, Sheppard, Kelsey and Friedlander have referred to voltage flicker caused by arc furnaces and the choice of reactance to minimize this problem. In my opinion the voltage fluctuations are produced by three distinct mechanisms: (a) partial and complete short-circuits and open-circuits of the arcs during the melting period, (b) arc re-ignition phenomenon, and (c) rapid dislocations of the arc and changes in arc length.

The magnitude of the fluctuations produced by (a) are great and are obviously governed by the maximum short-circuit current, which in turn is determined by the amount of reactance in the furnace circuit. However, since these disturbances occur erratically and can be of several seconds' duration, they are not of the type which produce intolerable voltage flicker.

The type of voltage fluctuations caused by (b) and referred to by Dr. Friedlander are illustrated in Fig. D. In this case also the magnitude of the disturbances can be reduced by increasing the reactance in the furnace circuit, but since they persist for only a few milliseconds and must occur at frequencies of 100–200 fluctuations per second, they are not significant.

The disturbances referred to in (c) are by far the most important and are due to sudden random variations in the arc due to changes in furnace atmosphere and arc supporting media.†

* BROWNE, T. E.: 'The Electric Arc as a Circuit Element', *Journal of the Electrochemical Society*, 1955, 102, p. 27.
† SCHWABE, W. E.: 'Lighting Flicker Caused by Electric Arc Furnaces', *Iron and Steel Engineer*, 1958, 35, p. 93.
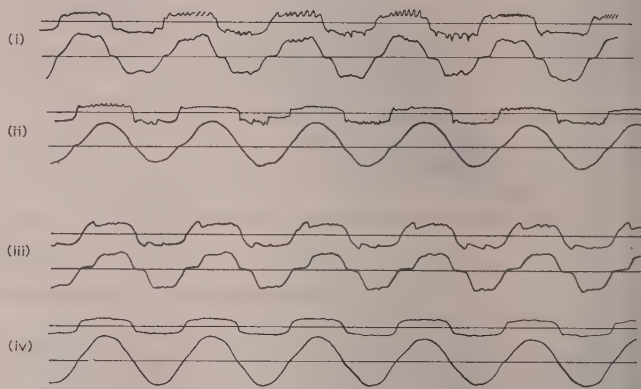
Fig. D.—Effect of circuit reactance on arc voltage and current waveforms.

Upper traces: arc voltage.
Lower traces: arc current.

(i) Low reactance, early stages of melting; 65 volts, 3 kA.
(ii) High reactance, early stages of melting; 50 volts, 3 kA.
(iii) Low reactance, flat bath; 65 volts, 3 kA.
(iv) High reactance, flat bath; 50 volts, 3 kA.

If the furnace circuit is highly reactive, the current changes caused by these arc disturbances will produce large reactive power swings and so cause excessive voltage fluctuations on the supply. For example, the reactive-power swing produced by a current change from 100 to 140% of the full-load value would be twice as great in a furnace of 60% total reactance than in a furnace of 30% reactance, both furnaces having the same rated apparent power. It is my opinion that these last-mentioned fluctuations are the ones which are likely to be cyclic in nature, and if they occur at frequencies within the range from 1/2 to 20 fluctuations per second they will dictate the effect of the furnace load on the supply network.

RADIOCOMMUNICATION IN THE POWER INDUSTRY

By E. H. COX and R. E. MARTIN, D.F.H., Members.

SUMMARY

The paper reviews the present position with regard to the uses of radiocommunication by the electricity supply industry and draws attention to some of the problems which have been encountered in the planning and operation of mobile and fixed v.h.f. radio links. The paper deals with this subject from a general point of view, since the wide variety of applications and special requirements cannot be dealt with in detail in a single paper.

(1) INTRODUCTION

Electricity has now become the prime energy source for all industrial and civil purposes, and since Vesting Day in 1948 the maximum demand on the electricity supply industry has increased approximately from 10 to 20 GW. This increase has resulted in a large construction programme and a corresponding increase in the number of consumers, necessitating a great improvement in communication for both distribution engineering control and consumer service.

The normal Post Office and private telephone networks, although originally adequate, were found to be not always able to cope with the increasing traffic economically, and it was necessary for the industry to look for some additional medium of communication which would be able to provide both links between fixed points and mobile telephony facilities.

The initial requirement was to establish mobile radio services for the operation of the power system, giving constant two-way mobile telephony communication between control centres and the engineers operating in the field. In addition to this, there was also a need to establish fixed-to-fixed radiocommunication links for services for which line circuits were either unsuitable or unobtainable. It was quickly realized that the advantages accruing to the operational side of the industry from the use of radio would help considerably in the consumer-service field. The consumer-service requirements are such that a rapid reply to complaints of consumers' supply breakdowns are given with the minimum use of transport and personnel.

The administrative arrangement of the industry, as planned on nationalization, provided for the establishment of Sub-Areas within the territory of an Area Board. In many cases the Sub-Areas coincided with the existing boundary areas of the power-system network, and it was possible to design a v.h.f. radio system which covered each Sub-Area from one or more transmitting points and enabled a common radio service to be given for the operational requirements and the consumer-service needs within each Sub-Area.

It is necessary that the fixed station or stations shall be adequately sited to give the maximum possible coverage in the desired area, and to achieve this result with v.h.f. radio it is often necessary to build the station on high ground remote from its associated control point. The control point may be connected to the radio station by land line, but—especially at the more

remote sites—land lines were not always available or practicable. For this reason it is then necessary to employ fixed radio control links. Other applications of such links arise in connection with the provision of emergency telephony circuits for control and administrative applications and also in the fields of telemetering, protection and remote control.

The applications of the m.f. and h.f. parts of the spectrum are well known and the limitations are such that these bands are, in general, unsuitable for the needs of the supply industry. The developments made in the v.h.f. part of the spectrum during the war were such that equipment became available in the immediate post-war years, and this part of the spectrum is admirably suited to the needs of the industry's mobile services. The use of the u.h.f. and microwave parts of the spectrum was considered, but, unfortunately, the development which had taken place at the time, especially in the u.h.f. band, ruled this out so far as mobile radio was concerned but showed that there would be a distinct possibility of use for fixed links at a later stage. Recent development of u.h.f. mobile equipment may enable such schemes to be set up where the more restricted coverage area is not a disadvantage. Some development of microwave equipment for fixed links has taken place, but this has been retarded by an unstable frequency-allocation policy.

The development of microwave techniques enables radio links to be provided for special purposes, such as protective-gear operation and the automatic location of transient faults on overhead lines, and although progress in other countries has been very rapid, it is only comparatively recently that experimental links for such applications have been set up in this country.

For the study of radioactivity levels at nuclear power stations it has been necessary to provide a mobile monitoring service, and use is made of mobile radio schemes for co-ordinating the work of these vehicles and enabling their movements to be rapidly directed in the event of an emergency requiring the use of the radiation-measuring equipment at the generating station.

In the event of a national emergency, when the likelihood of severe damage to the power network and the land-line system would be great, the use of radio for civil-defence purposes in the industry is essential, as are the similar uses by the military and other authorities.

Apart from the difficulties caused by the interruption of supplies, considerations affecting danger to life apply in the vast majority of the equipment employed within the industry, and these dangers may be greatly enhanced if reliable and instant communication is not available.

Following a supply failure, the restoration of supplies to consumers is of paramount importance, and this also involves safety to life and the protection of costly plant. The time involved in the restoration of supplies after breakdown can be considerably reduced by the use of radiotelephony, providing, as it does, a flexible and continuous communication scheme by which all work in a wide area can be co-ordinated.

Emergencies requiring the use of radio are often widespread (e.g. electrical storms) and result in sudden failures of essential services over very extensive areas. These services, which must

be restored without delay and therefore involve immediate action, concern water supplies, public health, hospitals, public transport, telecommunication, and every type of industry. In many instances coal mines and gas works are dependent on electricity supply, and in the oil and other processing industries, catastrophic losses can follow a prolonged failure of power and serious dangers can arise from the development of explosive conditions.

For the above reasons it is obviously essential that the highest priority should be given to the provision of reliable communications and that the communication scheme shall itself be independent of power-system failures. To achieve this, standby power equipment which automatically comes into operation under conditions of public-supply failure is installed.

(2) MOBILE SCHEMES

(2.1) General Considerations

For both consumer service and engineering work the mobile schemes should give the best possible coverage of the desired geographical area (which is dependent upon the administrative requirements). This coverage must be capable of providing a signal strength which is fully adequate for reliable speech communication in all places. Every endeavour is made to avoid blind spots by the use of careful transmitter siting and in some cases by the use of multi-carrier schemes. The reliability aimed at is such that an unfailing 24-hour service is given. Owing to these considerations, the degree of service aimed at in the system is greater than that required for ordinary commercial mobile radio services. This is realized by a consideration of the very large amount of capital invested in the plant of the industry, the satisfactory and continuous operation of which is vital.

The traffic density is dependent upon the requirements and the operation of the system. It is necessary to give instructions, often of considerable length, which have to be taken down by the recipient in writing and repeated to the control point to check correctness. The maximum traffic density is a function of the number of calls which can be set up in any one hour on the minimum setting-up time. Under serious system breakdown conditions the saturation of the network by engineering traffic is such that there is no time available for commercial consumer traffic to be imposed on the same channel. Likewise it is not possible, under the same principle, to establish shared-channel usage with other services. Traffic density is defined as the minutes of channel occupancy over a given period, either transmitting or receiving, expressed as a percentage of the number of minutes in the period. Experience has shown that traffic densities of 100% can be encountered over a period of 24 hours and 90% over 36 hours during the peak of system outages caused by storm conditions. On the consumer-service side it has been found that traffic saturation of 65% is being regularly achieved in some cases.

(2.2) History of Introduction of V.H.F. Radio in the Supply Industry

In 1946, when the Central Electricity Board was carrying out experimental work leading to the introduction of radio for mobile purposes, many tests were made in order to determine whether to employ a.m. or f.m. systems. At that time it was found that f.m. equipment gave a slightly superior range, but that in practice this was not always realized owing to the increased difficulty of maintenance. Past experience with both f.m. and a.m. schemes and comparative tests under carefully controlled conditions have indicated that there is little difference in performance between the two.

The principal advantage arising from the use of a.m. equip-

ment has been found to be the gradual decrease in signal strength at extreme range which enables a mobile station to move into an area of stronger field strength in order to achieve satisfactory communication when the mobile is called. With an f.m. installation the equipment tends to cut off rapidly at extreme range, and beyond this point no further communication is possible. F.M. equipment has some advantages over conventional a.m. equipment from the aspect of impulsive-noise pick-up at the receivers, although recent advances in noise limiters have improved a.m. equipment in this respect. The f.m. equipment is inclined to be more complex, particularly in the receiver circuits, and although the frequency-stability problems have been largely solved, frequency modulation cannot readily be employed for multi-carrier schemes. It has furthermore been found in the past that a.m. schemes are in general easier to maintain than f.m. schemes. For these reasons, nearly all schemes in the industry use amplitude modulation, although modern f.m. equipment is undoubtedly highly satisfactory.

In general, it has been shown that there is little to be gained by the use of an effective radiated power in excess of 15 watts, but that in certain cases it is desirable to employ an effective radiated power of 25 watts to give a signal strength sufficient to meet the demand of a satisfactory signal in the mobile receiver at extreme range in a given area. Post Office requirements in any case limit the effective radiated power to 25 watts. In many cases much lower powers are satisfactory, but in a few cases powers up to 50 watts have been required.

A basic single-frequency simplex system is shown diagrammatically in Fig. 1, where each equipment comprises a transmitter with a microphone and a receiver with telephone earpiece or loudspeaker. The transmitters and receivers are controlled in frequency by quartz crystals and are permanently tuned, without external adjustments being provided to vary the operating frequency f_1.

All equipments are normally in the 'receive' condition ready to accept any incoming transmission from another station. Since the frequency is common to all units, each unit can hear all others and cars can intercommunicate without the fixed station being operative. But because the transmitter and receiver of a given station are working on a single frequency, it is impossible to send and receive simultaneously. In other words, the equipment is suitable for simplex operation.

In practice this has several advantages, amongst which are reduced power consumption at the mobile station and inability to 'butt in' when receiving a message. The former advantage arises because a common power unit may be used to supply either the transmitter or the receiver, which are never required to be in simultaneous operation.

In practice it can be shown that it is advantageous to use simplex as described, but with '2-frequency working'. This is illustrated in Fig. 2, from which it will be seen that, since the mobile stations each send on frequency f_1 and receive on frequency f_2, they cannot communicate with one another but only with the fixed station. This is helpful in some circumstances, since it makes for good operating procedure in that all messages must be handled at the headquarters fixed station. It would appear at first sight that 2-frequency working is uneconomical in the use of frequencies, but when viewing a country as a whole and considering all the various users and the availability of frequencies, this is not the case.[1] It is also possible to repeat the channel allocations more often on a geographical spacing basis. In view of the relatively close spacing of frequencies resulting from the large number of users in the very restricted v.h.f. bands available for civil purposes, it is most desirable to avoid interference between schemes which may be not only for adjacent frequency channels but physically close to one another.
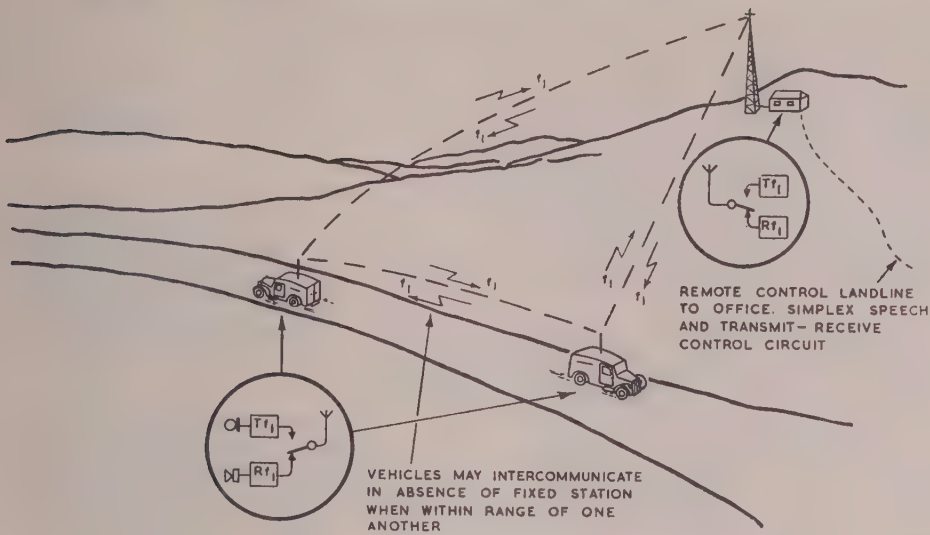
REMOTE CONTROL LANDLINE TO OFFICE. SIMPLEX SPEECH AND TRANSMIT— RECEIVE CONTROL CIRCUIT

VEHICLES MAY INTERCOMMUNICATE IN ABSENCE OF FIXED STATION WHEN WITHIN RANGE OF ONE ANOTHER

Fig. 1.—Basic single-frequency simplex system.

VEHICLES CANNOT INTERCOMMUNICATE DIRECTLY ONE WITH ANOTHER EXCEPT VIA FIXED STATIONS

REMOTE CONTROL LANDLINE TO OFFICE. SIMPLEX SPEECH, TRANSMIT—RECEIVE CONTROL CIRCUIT AND RE-TRANSMISSION SWITCH CONTROL

NON—STANDARD REVERSED FREQUENCY MOBILE STATION. CAN ONLY COMMUNICATE WITH STANDARD MOBILES AND WITH STATION VIA 'A' OR 'B' WHEN THEY ARE FITTED FOR RETRANSMISSION

STANDARD MOBILE STATIONS

Fig. 2.—Two-frequency working.

This applies particularly in large cities, where fixed transmitters of one scheme may be operating close to the fixed receivers of another, and unwanted interference may then be produced.

It is therefore the practice of the Post Office to allocate the frequencies available for commercial mobile services in Britain on a 2-frequency basis, except in special cases, thereby avoiding these forms of interference.

The disadvantage of the inability of mobile stations to inter-communicate directly can in some measure be overcome by the means shown in Fig. 3. The basic arrangement is exactly as in Fig. 2, but a switch is added at the fixed station to enable the receiver output to be connected to the transmitter input, arrange-

MOBILE A   MOBILE B   FIXED STATION
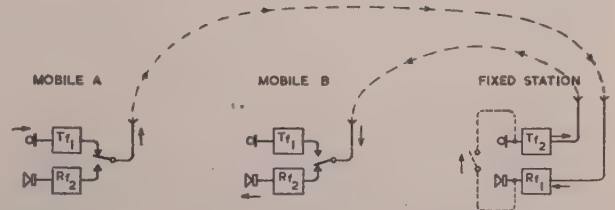
Fig. 3.—Talk-through.

ments being made to operate both simultaneously. With the talk-through switch closed the transmission from mobile station 1 on frequency f_1 is received at the fixed station, diverted through the switch and retransmitted on frequency f_2 by the fixed station transmitter. Since all mobile receivers are tuned to frequency f_2, intercommunication between mobiles via the fixed station is now possible. This facility is under the control of the fixed-station operator, who can close the talk-through switch when required. This is often advantageous where the fixed station is not manned at night, when the switch can then be left closed, thus enabling all mobile stations to intercommunicate on a breakdown job without any personnel to operate the fixed station.

One of the principal difficulties arising from the use of the retransmission system described above is that signals received at the fixed-station receiver on frequency f_1, owing to reception of transmissions from other areas using the same frequency, are liable to trigger the local transmitter and reradiate these transmissions on f_2. This causes the transmission of numerous spurious signals which result in interference with the mobile receivers associated with f_2 and the unnecessary occupation of the channel. For this reason it is preferable to use the retransmission facility only when it is required for direct communication between two mobile stations and to rely upon the use of land lines or fixed radio links for the remote control of the main fixed station, rather than the alternative of using a fixed station with reversed frequencies at the main station. Intermobile working can also be achieved by the use of a non-standard mobile station having reversed frequencies. This is also illustrated in Fig. 2.

By the use of a 2-frequency working scheme arranged for simultaneous transmission and reception on suitably spaced frequencies, full duplex operation is possible, as shown in Fig. 4. This enables interconnection to be made to a line telephone system, but for operational purposes in the industry, experience has shown that it is desirable for reasons of good operating discipline on mobile schemes to restrict access to one controller only. The disadvantages of full duplex operation include the necessity for increased power supplies in mobile equipment and the use of dual aerials or complex filters for common-aerial working. For these reasons, duplex installations for mobile working have been hardly used in the industry and are unlikely to find favour in the future for mobile schemes.

(2.3) Fixed Station for Mobile Schemes

While a single-fixed-station scheme may be adequate for, say, a 20-mile radius coverage in a large town or city, it may be inadequate to give proper coverage over a bigger area. In such a case it is advantageous to use the multi-station scheme, where two or more fixed stations are operated simultaneously. Such systems are now in wide use and have become known as 'multi-carrier' systems.[2-4] Fig. 5 shows such a scheme diagrammatically.

The arrangement employs two or more carefully sited fixed stations designed to give coverage to the required area. The scheme can be considered as being analogous to the shadowless lighting of a room by a number of small lamps rather than by the use of a central lamp fitting. Flutter effects due to field-strength variations at a moving vehicle receiver are minimized, and, since the coverage area is effectively 'floodlit', dead spots are reduced or eliminated. The fixed stations are quite standard, except that their respective transmitters are tuned to frequencies 8 or 10 kc/s apart (with 100 kc/s channel spacing). Multi-station schemes are possible with 25 kc/s channel spacing, but the frequencies cannot be offset as far as 8–10 kc/s. Schemes are now being commissioned with an offset of $4\frac{1}{2}$ kc/s.

Since both transmitters radiate the same intelligence simultaneously, it is possible that a suitably placed mobile station may be receiving a signal from both fixed stations at one time. The bandwidth of the mobile station receiver must therefore be wide enough to accept a transmission from either of the fixed stations without any adjustment being required. If two signals are being received at once, an a.f. heterodyne whistle is produced
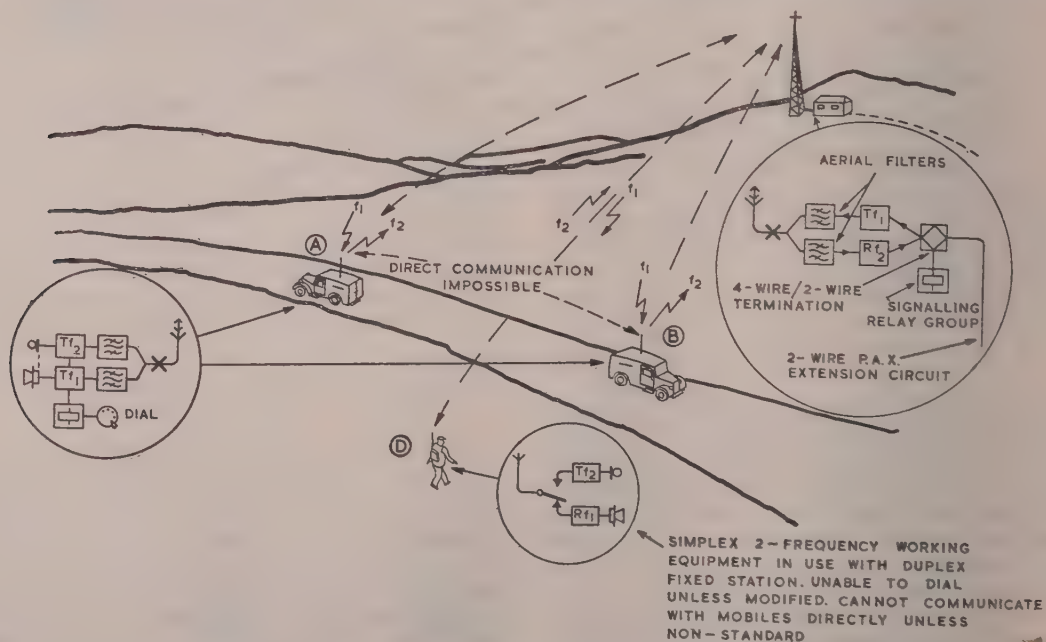
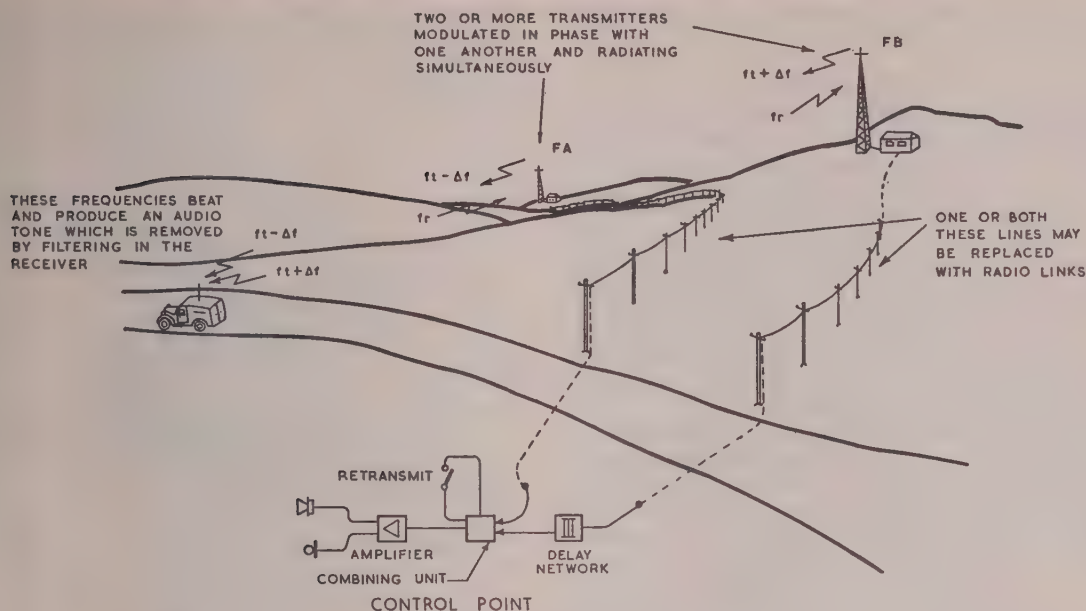
Fig. 4.—Full duplex scheme.

Fig. 5.—Multi-carrier scheme.

the mobile receiver, owing to beating between the two carrier frequencies. The frequency difference is therefore purposely chosen to cause this beat to lie at the upper end of the a.f. spectrum, and by means of a simple low-pass filter in the mobile receiver, the whistle is removed while the speech is left unaffected. To avoid distortion at the mobile receiver, the two fixed transmitters must be modulated in phase. The linking of the control point to the main station is often carried out with low-power fixed radio links, thereby avoiding difficulties such as phase equalization and reliance on long metallic circuits.

The fixed-station equipment is normally housed in an existing building or may require the provision of a small building or kiosk, which must be warm and dry. The aerial system is mounted on a mast or tower which is usually from 50 to 150 ft high. The correct siting is vital, and this fact has sometimes caused the premature condemnation of v.h.f. owing to tests from an inadequate site being disappointing. Ranges of 20 miles radius or more are obtainable under average site conditions (fixed station 200–300 ft above extremities of coverage area), and with good conditions it is not unusual to work over 50 or 60 miles. Even a radius of 20 miles will cover some 1 250 square miles, in which many thousands of consumers may be living.

The fixed-transmitter output is sometimes monitored by a directional coupler or by a small pick-up probe placed near the aerial, the v.h.f. signal being rectified and applied in the form of a direct current to a land line. A meter at the control position enables any deterioration in the transmitter output power to be detected. Monitoring receivers at the control position are also widely used.

Since it is usual to require maximum coverage in all directions from a fixed station, an omni-directional aerial system is usually employed. Directional aerials can be used to concentrate the radiation, as may be required at a station sited near the coast; this usually results in an improvement in service rather than an improvement in range.

The fixed and the mobile stations require to be well designed for continuous operation with a minimum of attention. Inter-Services type-approved components should preferably be used

throughout and the valve types should be capable of allowing easy replacement under emergency conditions. Equipments using 'Services preferred types' or 'special quality' valves are preferred for use by public utilities. Experience over the past few years has indicated that the electrical and mechanical design of radio equipment has been greatly improved to achieve better reliability and accessibility for maintenance. Although the majority of commercial and radio equipment has proved remarkably satisfactory, there is a good case for employing apparatus only of the very highest standard of construction, such as is commonly utilized by the Services, particularly on vital circuits such as may be employed for protective-gear operation, etc. By the employment of standard such as DEF 5000, it is hoped to achieve even better standards of reliability and ease of maintenance. Draft specifications covering components and constructional features have been prepared within the electricity supply industry and are now under discussion.

Since the fixed-station transmitters are often located in remote areas and derive their supply through considerable lengths of overhead line from the public network, and are furthermore always required for use at the time of failure of public supply, it is often necessary to provide an emergency power supply. This can take the form of a small rotary inverter driven from a low-voltage secondary battery which is normally trickle-charged from the a.c. supply. The failure of the local a.c. supply starts the machine automatically by means of a relay, so that the v.h.f. equipment remains operative. Alternatively, a self-starting liquid- or gas-fuel-driven generator can be employed. The availability of long-life dry cells or of solar cells, in conjunction with partly or wholly transistorized units, may enable low-power equipments to be operated in outlying places where no public supply is available.[5]

It is advantageous to notify the operator automatically at the remote control point that the power supply has failed and that the transmitter is operating on a standby supply. This has the added advantage that it also automatically notifies the operator at the control point of the failure of that particular part of the power-supply system. A warning device which injects an inter-

mittent 'pip' of tone into the transmitter a.f. input has been developed for this purpose.

(2.4) Mobile Stations

The mobile stations are generally similar to fixed stations from the electronic aspect, but their v.h.f. power output is restricted by the supply available. The typical mobile station employing thermionic valves consumes about 9 amp in the 'transmit' condition and 3 amp in the 'receive' condition from a 12-volt supply. Arrangements must sometimes be made to increase the vehicle's dynamo charging rate or alternatively to provide a separate battery. With equipments of the low-power dashboard-mounted type this is rarely necessary. Since the supply is generally 12 volts d.c. in a truck or private car, it is impracticable to provide for a v.h.f. output greater than about 15 watts. The consumption figures will be markedly reduced by the use of transistors in all or part of the equipment.

In mobile a.m. transmitters arrangements are often made to allow the modulator to be used as a public-address amplifier in conjunction with a hailer-type loudspeaker. This is often useful where instructions need to be passed to a construction crew working near the vehicle and for operations such as conductor sagging on transmission-line towers, etc.

The vehicle ignition system, dynamo, windscreen wiper, etc., generally need to be properly suppressed to avoid interference with the mobile receiver. In some cases it is found that attention should, in addition, be given to seeing that all rubbing parts, i.e. bonnets, boot covers, etc., are properly bonded with flexible copper braid.

(3) FIXED SCHEMES

Reliable communications are, of course, essential for the satisfactory operation of a large high-voltage interconnected transmission network. The control rooms must be in contact with all generating stations and major substations in their respective areas, and this alone necessitates a complex telephone and telegraph network. Furthermore, the operation of the system requires the telemetering of various quantities from the many remote points to the control rooms via communication circuits. Other requirements for communication circuits arise from the operation of protective and supervisory gear of various types.[6] In Britain, the line circuits are, in general, readily available, since a complex public network already exists, but there may nevertheless be cases for the use of radio in certain circumstances.[7, 8]

In the same way as the large transmission network, the lower-voltage distribution networks which individually cover a smaller area require an adequate communication system. The networks differ from the national transmission system in that there are very many substations and load points. The national line-telephone network cannot economically or physically provide the service which is required at the prodigious number of points. Requirements basically similar to those on the transmission network for telemetering remote control and protection exist on the distribution networks. Although the industry has only limited permission (except experimentally) to operate a radio circuit unless one or both ends are fully mobile, considerable experimental work is being carried out to investigate the suitability of radio links in replacing line circuits for telephony, telemetering and protection.

In America, Sweden and other countries, the use of fixed-point radio circuits by the power industry is accepted and many installations are now in use. However, they should be used only where a definite advantage can be shown, either in the physical arrangement of a scheme, in cost or due to some other special consideration such as the bandwidth of the channel required.

The radio link is not subject to failure due to natural causes such as storms, snow, etc., and does not have the limitations of the power-line carrier.

A typical case where radiotelephony could be advantageously employed is illustrated in Fig. 6. Each generating station is
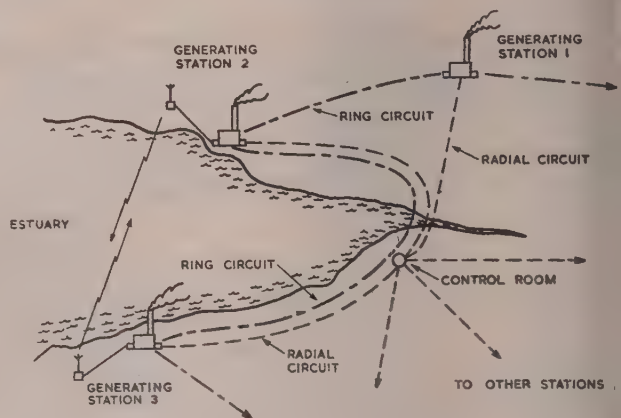
Fig. 6.—Inter-power-station working.

provided with a direct-wire circuit radiating from the control room. Security is achieved by linking the generating stations by a ring circuit. This principle is satisfactory until there is a river estuary in the position shown. The ring circuit between No. 2 and No. 3 generating stations must follow the same route as the two radial circuits and it may even have to pass via the same Post Office exchanges or through the same multi-core cables. The extra security is now jeopardized and could be regained by the use of a simple radio link across the estuary in the position shown. There is also a case for reinforcing certain radial circuits with radiotelephony links. An example of an actual emergency application in this field was the complete control of a 285 MW steam station when all line circuits were put out of action by flood damage. Control and ordering of spares and replacements were carried on over a radio circuit, which enabled the plant to be run normally. Such circuits would preferably be operated initially in the v.h.f. range. The cost compares very favourably with a line, and commercial equipment is available which will give the equivalent of a 4-wire telephone circuit with signalling facilities for dialling, etc. The use of low-power transistorized v.h.f. repeaters would enable such links to be extended for 100 miles or more without difficulty. The repeaters can be made in a very economical and compact form and can be supplied from dry cells or a secondary battery charged from the daylight.

A common aerial is sometimes employed in place of separate aerials for simultaneous transmission and reception on the two frequencies, coaxial filters being introduced to enable both the transmitter and receiver to be connected to the one feeder. The advantages are: (a) lower ultimate cost than a rented line. (b) less liable to interruption by war damage, floods, storm, etc. (c) faults will be in apparatus under direct control of one authority; and (d) less liable to inadvertent interruption than line circuits.

Another application of radio is in the protection field, where a signalling circuit is often required between two substations. This application is in some ways similar to the use of a power-line carrier for the same purpose, except that it is not prone to interference from disturbances on the power line itself and it can be very much cheaper to install.

The main difficulty lies in the availability of frequencies in the already congested civil parts of the v.h.f. spectrum and in the difficulty of working a sufficient distance for applications on the main transmission network without the use of relay stations. There are certain cases where a workable path for a protection link exists in the v.h.f. spectrum, and very often these paths will be across water to islands or across rivers and bays where a direct metallic line circuit may be impracticable. The radio link could then be used to transmit intertripping, impedance-protection acceleration or phase-comparison signals for use with power-system protective systems working on these principles.

Relay stations, although technically possible, suffer from the disadvantage of requiring a reliable power supply to energize the radio equipment during fault conditions in the main network. As has been mentioned, this may well be overcome in the future by the use of solar cells to power the repeater station. This problem also applies to the terminal stations, but in this case non-interrupted power supplies will often be already available. In the distribution network, however, the distances involved are usually smaller and in many cases the use of relay stations will be unnecessary.

One of the great advantages of the use of radio for a phase-comparison protection link lies in the absence of variable phase-shifts which limit the performance of certain schemes when operated through line circuits.

The 3-phase currents can either be summated and used to control the transmission to the remote end or the positions of each of the three phases could be sent simultaneously over the same radio-link equipment for comparison at the far end. Such schemes require to be arranged for simultaneous duplex operation, so that at both ends of the power line it is possible to make a phase comparison between the local power currents and those at the remote station. Under normal load conditions the currents are substantially in phase, but with a fault in the protected zone they become in anti-phase. Radio systems working on these principles have been tested on a laboratory basis and an installation has been made. Special circuits have been devised to take into account the conditions when one end of the power line is switched out, giving no line current at that end and capacitance currents at the remote end. Since the equipment is fundamentally electronic, the phase comparison is also carried out with valve circuits which are all arranged to fail to safety by giving a fault alarm and not an erroneous tripping operation. In a recent experimental equipment known as 'transiphase', all functions except those of the radio link proper are carried out by transistors.

It is sometimes necessary to establish the actual phase angle between the high-voltage system voltages at two widely separated points on the network, under both steady-state and transient conditions. In such cases the reference phase is transmitted by radio for comparison at the receiving end, the instrumental errors being first measured by bringing the transmitter and receiver together initially. A line is, of course, unsuitable for such a purpose unless the phase shift is known and remains constant during the experiment.

Since all previous experiments were made using v.h.f. equipment working in the ranges 70–90 or 170–190 Mc/s, it was decided to investigate the possibility of using higher frequencies, where the spectrum is not so congested and wider bandwidths are available. The first frequency band to consider is in the vicinity of 460 Mc/s (70 cm) and experiments have been carried out with equipment operating at this frequency.

Several hundred microwave links, i.e. links working on centimetre wavelengths, are in use by the power industries in America and many other countries.[9–12] Such equipment is capable of linking points along optical paths by means of a low-power

highly directional beam of radiation. These frequencies are unaffected by man-made interference, but fading can arise from atmospheric conditions.

An experimental system under construction for trials in the industry is arranged for operation in the $7 \cdot 3$–$7 \cdot 4$ Gc/s region and will be available in two versions for ranges of 4 and 16 miles or more. It is designed for a fade margin of 30 dB and a 99·9% reliability factor and provides for the use of tower-mounted passive reflectors to enable the equipment itself to be kept near ground level, in order to facilitate maintenance. The link will have full duplication of electronic equipment with automatic change-over in the event of failure, and will be designed to provide a single duplex telephone channel, two 3-phase comparison channels for power-system protection purposes and a number of intertripping and remote-control channels.

Because of the widespread line system and frequency-allocation difficulties in the past, multi-channel links do not at present find any wide application in the power industry in Great Britain. It is possible that simpler versions might be useful, particularly in special cases such as the proposed cross-Channel cable or if it is desired to install automatic fault-location equipment on the 275 kV system. It is likely that complex systems will ultimately be employed, particularly for data handling.

(4) FREQUENCY ALLOCATION

(4.1) Frequencies for Mobile Systems

The electricity supply industry originally consisted of a very large number of small undertakings, and thus the problem of allocating frequencies for the use of the industry was not tackled as a single problem at the outset. A number of frequencies were allocated at various points in a band reserved for commercial users. This band is now very overcrowded and it cannot be extended in either direction, owing to allocations which have already been made. It has been proved that the number of frequency allocations made by the Post Office on the basis of a range of 15 miles are completely inadequate for the requirements of the industry. Experience has shown that, in order to obtain reasonably interference-free operation between areas using the same pairs of frequencies, a geographical spacing of at least 80 miles between two fixed stations using the same channel but forming part of two individual schemes is essential.

The industry has co-operated with the other fuel and power industries (i.e. coal and gas) in the investigation of the frequency-allocation requirements and has produced a plan on the basis of 80-mile spacing of fixed stations, sharing frequencies where possible and taking into account the administrative boundaries and the geographical barriers, which has in the main been agreed with the Post Office. The original plan was based on the allocation of two frequency channels in the 80 Mc/s band and three in the 170 Mc/s band. This plan has now been shown by experience to be inadequate for the industry, even though the geographical barriers have been used to the maximum advantage. Considerable interference between stations sharing the same channel was being experienced and this interference has been enhanced by the use of reversed-frequency control links.

The curves shown in Fig. 7 indicate the rapid rise of the use of radio equipment in the power industry, from which no falling off can yet be seen. It is now known that the fuel and power industries require at least 26 frequency channels for mobile use, of which the electricity industry requires 14, and these should preferably be situated in a continuous block of the frequency spectrum. It cannot be emphasized too strongly that the needs of the fuel and power industries are such as to warrant a special section of the frequency band being made available for their exclusive use outside the commercial users' band.
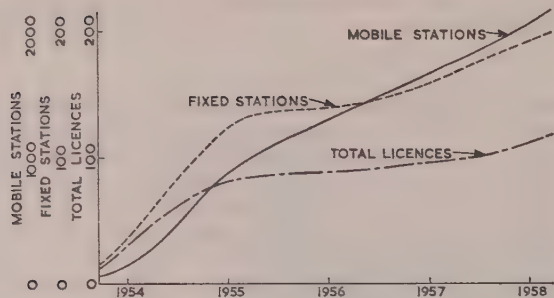
Fig. 7.—Growth of radio usage.

The operations of the Generating Divisions of the C.E.G.B., as opposed to the Electricity Boards, require single-frequency-working mobile schemes for use on high-voltage-line repair and construction work. The mobile stations may often be out of range of their base stations but in touch with mobile stations of another Division. It is most probable that the present increasing development of the Divisional single-frequency schemes will result in extensive mutual interference and that it will eventually be found necessary to change to 2-frequency working on two or more channels to avoid such interference problems. Until a change to 2-frequency working on a sufficient number of channels for the Divisional Grid maintenance schemes can be made, all fixed-station transmitter/receivers of the existing single-frequency schemes should be modified to minimize such interference. The modification comprises the connection of a spare pair of contacts on the receiver muting relay in series with the station press-to-transmit key. By this means the operator cannot bring his transmitter on if the receiver is already receiving sufficient carrier from a remote transmitter to open the muting system. Such a modification would do much to reduce interference but cannot be regarded as a final solution to the problem.

The vital role occupied by the fuel and power industries in the economic life of the nation makes it essential that in the use of radio they should be able to plan ahead. To this end a clearly defined policy for frequency allocation is being formulated which can be applied now and in the future.

(4.2) Fixed Services

The electricity supply industry has been endeavouring to establish fixed services on an experimental basis since 1938, but owing to changes in the frequency-allocation policy, little progress could be made in this direction until comparatively recently when a microwave frequency in the $7 \cdot 3$ Gc/s band was made available, subject to certain limitations as to its use. There is, however, a considerable requirement for the use of fixed links in the 170 and 450 Mc/s bands for various purposes, such as emergency telephony circuits, substation alarms, remote-control telemetering and protective-gear schemes.

In both mobile and fixed radio the frequency-allocation situation in some other countries is far more favourable than that in Britain. For example, in the United States the Federal Communications Commission publish clear rules which lay down the frequencies available for both mobile and fixed services in the 'Power Service' which forms a part of the industrial radio service.

The lack of allocations for fixed services for essential requirements in this country has held back the development of specialized equipment which the manufacturers might otherwise have been able to offer to oversea countries.

Similar difficulties are encountered in a few of the Western

European countries and as a result O.E.E.C. have emphasize the urgency of this problem and asked members of the organiz tion to allow sufficient frequencies to be allocated for the excl sive use of electricity systems. It is considered that there is good case for a review of the whole question of frequency alloca tion in the v.h.f. and u.h.f. bands which would include a investigation into the actual usage of the bands.

(5) MAINTENANCE

Electronic equipment will undoubtedly find wider uses in th power industry, and it must be remembered that it is no possible to produce an equipment with excellent reliability eve under adverse conditions such as are met with in mobile servic But not even the best equipment can be expected to give goo service without regular routine maintenance. This is facilitate in many commercial equipments by mounting the apparatus o plugs so that sections of it can be withdrawn from service an replaced as required. It is considered that the reliabilit requirements of equipment for use in the industry in many case justify the extra cost of using equipment built to inter-Servic or other comparable standards.

(6) 25 kc/s CHANNELLING

Owing to the enforced restricted spectrum space available t the commercial users in the v.h.f. band, it has become necessar for the manufacturers to develop equipment having the poss bility of providing a narrower channel spacing. Equipmen capable of giving a channel spacing of 25 kc/s is now com mercially available, and many schemes using this equipment a already in operation in the power industry.[13] The use of 25 kc channelling has been found to offer no particular difficulties in scheme with a single fixed station, and developments are procee ing with multi-carrier schemes. This is being achieved wit staggering of $4\frac{1}{2}$ kc/s and with the necessary frequency stabilit In order to minimize the nuisance of the audible beat note, th receiver has been designed to ensure that the level of the 4 kc beat will be at least 30 dB down on the desired audio signa The degree of crystal stability in such equipment of multi-carri schemes is of paramount importance, but it is believed that th problem has been solved by the use of oven control and moder crystal-oscillator circuits so as to produce stabilities of the ord of $\pm 0 \cdot 000 3 \%$.

As a direct result of the shortage of channels formerly availab and the availability of satisfactory 25 kc/s equipment, the ele tricity industry in Britain has now embarked on a 3-year pr gramme during which time every mobile station (more tha 2 000) and fixed station (more than 220) will be changed to 25 kc channelling. This will enable the spectrum space between th original 50 and 100 kc/s spaced channels to be more ful exploited and will bring all the installations into line with th Post Office requirements for 25 kc/s channelling.

Since the frequency allocations have been dealt with on common basis for coal, gas and electricity, similar consideratio (although in smaller numbers at present) apply to the equipme in use in the coal and gas industries. Even in countries whe frequency allocation presents no problem at present, the adve of 25 kc/s channelling equipment is important, because it often found that congestion will be occurring in a few years. is considered that the narrow-channel-spacing equipment shou be employed, even in an isolated scheme, because it is alwa likely that a second scheme may be required in the same pla in a year or so. The original choice of such spacing equipme may permit a second scheme to be fitted in, whereas with wid channel spacings of 50 or even 100 kc/s there may be insufficie spare channels available.

Central Electricity Research Laboratories, for permission to publish the paper.

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DISCUSSION BEFORE THE SUPPLY SECTION, 16TH NOVEMBER, 1960

Mr. G. F. Peirson: At meetings which have been held between representatives of the electricity supply industry and the Post Office we have been impressed with the need to conserve radio channels, and the Electricity Boards have always planned to make the maximum use of the fewest channels necessary to achieve the relatively interference-free performance in communication which is vitally necessary for safety to men working on high-voltage systems. Moreover, the Boards made the maximum use of channel space by installing only 25 kc/s equipment, when 100 or 50 kc/s was permitted by licence, and at a time when this could be obtained from only one or two manufacturers. The space so created enabled the Post Office to satisfy some of the industry's needs for additional channels. This policy was notified to and accepted by the Joint Radio Committee of the Nationalized Fuel and Power Industries and was recommended to its constituent members and adopted by them. We are not completely altruistic in this. The second report of the Mobile Radio Committee dealt with the reduction of the channel width in the 180 Mc/s band from 100 to 50 kc/s. We did not relish the idea of changing to 50 kc/s equipment and then having to change later to 25 kc/s, with its attendant expense, particularly when it was possible to install 25 kc/s equipment initially. Later reports of the Mobile Radio Committee have only served to indicate that we were right.

In Section 4.2 the authors say that there is a good case for a review of the whole question of frequency allocation in the v.h.f. and u.h.f. bands. Do they believe that use is still being made of bandwidths greater than are necessary in view of the satisfactory experience of the use of 25 kc/s in our own services, and is there still an unnecessary and therefore wasteful use of the r.f. spectrum?

Reference has been made to the use of radio in emergencies to deal with failures of the supply over wide areas caused by electrical storms. In the Midlands we find that lightning storms travel up the Severn estuary and disrupt our supplies in the Gloucester Sub-Area, then up the Severn valley through the Worcester Sub-Area, and then to Shropshire and Herefordshire,

so that there may be three Sub-Area system controllers wit trouble and the need to communicate with repair parties an engineers to restore the supply. All must work simultaneousl and independently of each other, which emphasizes the need fc interference-free radio operation. In the Worcester Sub-Are alone we have had 157 reported failures of supply in 3 hours i one evening, which will give an idea of what is involved.

I agree with the authors that there is now little difference i performance between f.m. and a.m. systems. I still conside that the advantages of amplitude modulation listed in Section 2. make it the obvious choice for communication with mobile since frequency modulation presents difficulties for multi-carri systems, but I would give serious consideration to its use fc fixed-to-fixed communication.

Reference is made in Section 3 to fixed schemes. The M.E. has a phase-comparison line-protection system on the Iro Bridge to Weir Hill 33 kV line. The ends of this line are rough 14 miles apart and the radio link is on a channel in the 180 Mc band. The equipment was given the necessary trials for abou 12 months, during which it was prevented from tripping th circuit. It was found to be stable and capable of operatin correctly on both in-zone and out-of-zone faults and was there fore put into full commission on the 6th October, 1959. Sinc then there have been six correct operations and no incorrect one

Substation control is mentioned in Section 7.2, but th authors refer only briefly to a use for radio which will grow importance over the years, just as has our use of v.h.f. radi for communication with mobiles. It will improve the qualit of our electricity supply service, particularly in the more remo parts of our areas, since instead of having to wait until som consumer lets us know that he has no supply, the remote sub station will immediately indicate at the control centre the circu or circuits affected. The control engineer can then take remedi measures forthwith, even to the extent of operating circui breakers by radio in the station affected or in other station which are radio-controlled, without the need for a visit t them. It is obvious that valuable time can be saved in this wa

that the energies of engineers can be conserved for those ...es which do not respond to radio treatment.

Mr. T. T. Bell: I appreciate the value of these radio equipments ...l the service which they can give to supply engineers, but not ... wide discrepancy between the importance of the services ...dered and the unbearably tight price limits imposed for the ...pply of the equipments in question. This point is referred to ...efly in the paper and mention is made of the availability of ...tain commercial equipment which would hardly be good ...ough for the purposes under discussion. Particular reference ...made to the possibility of applying Service standards to the ...uipment.

There is a very wide difference in price between the mobile ...uipment which may be used by less important services and ...uipment needed for the control of large amounts of power in ...cumstances which may involve the safety and even the lives ... human beings. It would not be inappropriate to have in ...nd a factor of 2 : 1 when considering the difference between ...se categories of equipment. In the future, with difficulties of ...commodating more channels, restricted available bandwidth ...d the possibility of the use of centimetric equipment, the price ...ctor will become much more important.

...ff we carry the idea of the number of channels to its logical ...nclusion and if single speech circuits are all that is required ...r mobile working, it is important to consider the possibility ... a bandwidth smaller than 25 kc/s. Work is now proceeding ... $12\frac{1}{2}$ kc/s systems, which should bring further advantage in ...ailability of channels.

The f.m./a.m. controversy is one on which there has been ...nsiderable discussion over the years. I think it is now ...cepted that the difference in performance in the field between ...m. and f.m. systems is sufficiently small not to be of paramount ...erational significance. For the fairly widespread system over ...nges of 12–18 miles some still feel that f.m. has advantages. ... reduction in flutter in the signal received at a moving vehicle ...n very significantly improve the readability of signals. While ... is accepted that at the extreme range an f.m. signal decays ...uch more rapidly than a similar a.m. one, the importance of ...adability of signals at closer range must not be overlooked.

...Finally, if immediate change-over from a mains supply to ... ttery standby supply is essential, it is necessary to avoid the ...nning-up time of the rotary machine, and the use of transistor ...wer units can be advantageous. If point-to-point links are ... be used for digital data transmission, the ability to change ...er without any significant break in the transmission becomes ...uch more important.

Mr. J. R. Brinkley: The development of mobile radio in this ...untry owes a great deal to the electricity supply authorities, ...d the planning of frequencies has been carried out in an ...derly fashion, to the great benefit of the users. At the same ...me, they are to be congratulated for their early introduction ... 25 kc/s channelling at a stage when its feasibility was still ...ntroversial.

...The authors have raised the question of reliability, but fault-...te statistics would have been valuable. Our service organiza-...on, which maintains many thousands of mobile equipments ...roughout Britain, keeps fairly comprehensive records. The ...ult rate varies with the application, but a typical figure would ... 3·5 faults per mobile per annum, mainly valve and component ...ilures. The components used are always the best available ...d conservatively rated. Improved reliability therefore turns ...rgely on improved component supply, and the equipment ...anufacturer is limited in his ability to effect rapid improvements ... fault rate by the quality of components available to him.

...While the progress made in mobile radio has been excellent, ...e use made of microwave radio by electricity authorities has been very disappointing. Frequencies and excellent equipment are available, but as yet there is no important microwave exploitation. This situation compares very unfavourably with contemporary developments in, for instance, Germany and Japan.

Mr. J. Pierson: In view of the shortage of frequencies the use of u.h.f. working suggests itself for mobiles. Field trials suggest that the range may be a little less and the fades both sharper and deeper than with v.h.f. operation; more care is also required in the siting of fixed station aerials, but surprisingly good results have been obtained in built-up areas, where signals tend to be reflected from buildings and make it possible to work round corners, etc. There would appear to be a case for using u.h.f. equipment for local schemes, leaving the v.h.f. system for the more difficult areas.

For fixed links, u.h.f. working permits high-gain narrow-band aerials, which minimize interference with adjacent schemes. Being discrete elements they possess low windage and present few mounting problems. Circuit-wise the equipment is largely conventional and does not call for expensive valves and waveguides.

Radio links have the great advantage that the equipment is entirely under the control of the operator and he is not dependent on other authorities in the event of failure. The fault can rapidly be located and rectified. Using standby equipment with automatic change-over it is possible to obtain 99·9% reliability, and this can also be increased by the use of transistorized power units run from float-charged batteries. This produces a genuine no-break supply, which is essential if digital information is being transmitted.

Mr. J. W. Dillow: The case for mobile radio has, I think, been established and it speaks for itself, but I am far from sure about fixed links. Unfortunately, power stations have a large demand for water and this leads to their siting in valleys. To ensure u.h.f. transmission out of the valley it is necessary to place a repeater station on the nearest hill-top, which must, I think, detract from its reliability and undoubtedly increases its cost. Alternatively, if the power station is on an estuary, there is trouble from fade-out over water.

The private network available to the C.E.G.B. from the Post Office is worked on the basis of mutual understanding. The Post Office know that if the power fails their batteries will be fully discharged in a few hours. In 1959 the average time for which a Post Office line rented by the C.E.G.B. was out of action was 15 hours, which is an extremely good figure of reliability. The Board rents approximately 1 100 circuits with a route length of 12 000 miles.

Mr. F. W. Gee: If the relationship between quality and price can be established—and I do not see why it should not be—it is a matter of arithmetic and not of opinion to choose the right equipment and avoid both the waste of money which occurs from buying better equipment than is necessary and the loss of money arising from using equipment which is not good enough. It should never lead to a quarrel between user and maker, because the data are there on which to base a logical decision.

Mr. A. J. Davidson: A recent development of link operation in a 3-station diversity scheme is the combined use of directional links for incoming traffic from the remote base stations and the reverse-frequency technique for outgoing traffic from control. In this way it is possible to reduce the number of additional link frequencies required to three and at the same time effect a substantial saving in the link equipment. Since this arrangement retains the normal operational requirements of local talk-through at the remote base stations (i.e. for vehicle to vehicle or sub-control to vehicle), allows the cutting-out of a static-affected base station and achieves economy in frequencies, it may be the most satisfactory solution yet considered.

With reference to 3-station working, it has been stated by one reputable manufacturer that the short-term stability of a fixed station transmitter is of the order of 5 parts in 10^6, and if the condition occurred that the drift of the three transmitters was towards one another it would be necessary to restrict the audio bandwidth of the mobile receivers to about 2 kc/s. This in itself can produce operational difficulties in that the drastic restriction in bandwidth will make it difficult for operators to recognize a particular individual's voice—a factor which may have some importance when, for example, switching operations are being carried out. Also, in order to achieve the low bandwidth, *m*-derived filters will be required and not the simple low-pass filter mentioned by the authors. It would be possible to accommodate such a filter inside a 15-watt mobile, but with a 5-watt mobile it would be necessary to fit it somewhere external to the set—a most unsatisfactory solution. Another difficulty may be the effect of intermodulation between the beat frequencies produced by the offset carriers in cases where a mobile is receiving all three fixed stations. A satisfactory solution to the 3-station scheme is awaited with interest, since the determining factor will be the short-term transmitter stability of fixed station equipment.

Referring to the use of frequencies in the 7·3 and 7·4 Gc/s region, a case might be made for s.h.f. links for single- or low-density-channel working, taking into account the use of passive reflectors which considerably affect the economics of a radio transmission scheme requiring a strategically placed repeating station to achieve the overall link. Present-day u.h.f. and s.h.f. costs seem to indicate that a passive-repeater s.h.f. link could compare favourably with an active-repeater u.h.f. link. Indeed, passive-repeater s.h.f.-link operation might make possible in mountainous terrain a fixed radio-link which could not otherwi[se] be provided.

Mr. G. S. Buckingham: The best possible advertisement f[or] electricity supply, by which we all live, is to have a continuo[us] and secure supply always available. Experience over the la[st] dozen years or so has shown that this can be vastly improve[d] by the use of radiocommunication from central points [to] vehicles fitted with receiving sets in the field. We make co[n]siderable use of it to keep the supply available to our consume[rs] in all sorts of emergency, including climatic emergencies suc[h] as lightning, floods, fog, etc. Credit must be given to man[u]facturers for close co-operation with the supply industry [in] improving the performance and reliability of mobile radio se[ts] and for still further developments which we seek in the future.

One of the themes running through the paper is the shorta[ge] of wavelengths available to the fuel and power industries. The[se] are public utility industries whose service depends on goo[d] communications, yet when they asked for an additional alloc[a]tion of channels they found they had to give up one 100 kc[/s] channel to get two 25 kc/s channels. The total spectrum wid[th] in use is therefore less than before and the new channels a[re] more difficult to work.

What is needed is a substantial portion of the radio spectrum, say 1 000 kc/s, divided up for use by the fuel and power industri[es] to the maximum advantage of the public. This might be mo[re] in the public interest than 200–300 new local broadcasti[ng] stations suggested for towns with populations of 50 000 peop[le] for disseminating local news and entertainment.

NORTH-EASTERN CENTRE AT NEWCASTLE UPON TYNE, 21ST NOVEMBER, 1960

Mr. G. W. B. Mitchell: On the Kariba system in Africa the 330 kV overhead lines traverse hundreds of miles of virgin bush country along easements cut through the bush, and there is very little road access to these. Owing to the distances involved it is impossible to use v.h.f. communication between fixed stations and line maintenance vehicles, which must largely use the rough easements as roadways. The frequencies used are in the 3–5 Mc/s range, and any one of a number of frequencies in this band can be chosen at will to overcome fading conditions as far as possible.

There is little similarity to the British Grid, where the e.h.v. systems, within the Divisions, link major power stations and substations which, typically, may be only of the order of 20 miles apart, and which, owing to the existing large Post Office communication system, can be suitably controlled by hiring Post Office circuits. In general also, the distribution systems covered by the Area Boards in this country are of greater complexity than many of those oversea, and their mere size alters the parameters of the problem as compared with those frequently occurring abroad.

It is interesting to note that nearly all the radio development discussed by the authors has taken place within the past seven years, and I agree that the slow start in this country has, in the past, largely been due to difficulty in obtaining frequency allocations. Another cause has been the ignorance of most power-system engineers about electronics. However, this state of affairs is changing fairly rapidly and the modern generation of power engineers is, of necessity, becoming much more electronically minded.

Looking at the world picture, I think there is a great need for the development of reliable multi-channel microwave systems, using as many unattended repeater stations as may be necessary. The advent of transistors and solar batteries should accelerate this development. In the past it has been held back by the high cost of getting power supplies to cross-country repeater station[s] particularly abroad.

I suggest that more use should be made of photo-facsim[ile] reproducers for conveying messages, since these are now qu[ite] transportable. The advantage of these instruments is that t[he] message can be typed out and checked before being sent a[nd] the overall time saving is considerable, since there should [be] little need to check back.

Mr. A. M. Stevenson: How do the Post Office measure t[he] effective radiated power referred to in Section 2? The electric[al] power fed to the aerial (and this is the usual method of describi[ng] the power of a transmitter), does not include the loss in t[he] coaxial feeder, which, if 120 ft long and of standard construction, may have a loss of 3 dB, so that half the power is lost in t[he] feeder. The aerial itself may be considerably inefficient co[m]pared with an omnidirectional stacked dipole. It therefo[re] seems that, using a standard-type feeder and aerial, the [real] power from the transmitter could be in the region of 100 wa[tts] and still comply with Post Office regulations. This addition[al] power could be useful on circuits which would otherwise [be] unacceptable, or at least in certain cases used to improve t[he] signal/noise ratio.

How do the authors assess the practicability of v.h.f. radio [in] a required area? It has been suggested that 'line of sight' [is] the only reliable method or by drawing a contour section [of] the area and allowing for the curvature of the earth, if t[he] distance involved is over 20 miles. In certain instances in t[he] Division (North East Central Electricity Generating Boar[d]) links which would appear difficult or impossible have giv[en] strength-3 signals on field trials. Could these results be d[ue] to temporary atmospheric conditions, such as temperatu[re] inversion?

Section 3 states that the radio link is not subject to failu[re] due to natural causes, such as storms, snow, etc. An aer[ial]

or 150 ft high would appear vulnerable to lightning. In process of catering for the protection of the aerial feeder, uld the authors recommend any special precautions, such as ng insulators in the metallic staywires?

Mr. W. Brittlebank: In Section 7 no mention is made of the are use of radio link techniques for hydro-electric power ions which is being considered by communication engineers. tomatically controlled generators and switchgear in power ions, normally in the same catchment area, are controlled group control centres. For short distances we use tele-one cables, and for longer distances voice-frequency tele-phy on power-line carriers superimposed on the main power es.

The use of u.h.f. radio links for the distances of 6–20 les encountered oversea appears advantageous from the cost ect. Are there any alternative views on this subject? In dro-electric work the u.h.f. radio links often run alongside

the shore of a reservoir level because of the easier line-of-sight aerial. Does the water cause any channel distortion due to reflection of the links?

I gather that there have been a number of experimental links on microwave techniques recently. A test between Errochty and Port-na-Craig, which is a group-control centre of the North of Scotland Hydro-Electric Board, was conducted with encouraging results, and a major high-voltage substation of the C.E.G.B. shortly to be commissioned and the television links are notable examples in this country. Do the authors favour more tests on microwave links in this country, bearing in mind the cost, or should they have the longer distances for Common-wealth transmission problems? The increase in frequency gives a narrower beam obtaining a higher gain with smaller aerials for the increased distances of such techniques.

[The authors' reply to the above discussion will be found overleaf.]

SOUTH MIDLAND CENTRE AT BIRMINGHAM, 5TH DECEMBER, 1960

Mr. J. C. Cluley: It is evident that the fragmentary nature the electricity supply industry before Vesting Day precluded her a comprehensive frequency allocation plan for the entire untry or a joint application for the requisite channels. though much progress has since been made, the industry s not invested in radio equipment to the same extent as have ny oversea supply authorities. This is partly due to the arcity of bandwidth in the crowded radio spectrum, and the thors have established a strong case for a much more nerous allocation of channels to the fuel and power industry. I feel that the authors have considerably underestimated the vantages of frequency modulation for mobile radio equipment, rticularly from the aspects of signal/noise ratio, transmitter iciency and the reduction of co-channel interference. Although e noise-limiting circuits generally fitted to a.m. receivers may duce the effects of impulsive interference, they cannot be as ective in this respect as those in f.m. receivers, which should nove all traces of amplitude modulation.

The commercial side of the industry is starting to use digital mputers for central accounting; if this trend continues, high-pacity data-transmission circuits will be required, particularly r systems in which most of the records are maintained by the mputer and can be interpreted only by the computer. The cessary wide-band channels can be provided most economically microwave radio links, which could also handle simultane-sly other narrow-band signals. Such a scheme would also able the supply industry to control more directly than at esent its own communication network, and, on the basis of merican experience, obtain greater reliability.

Looking well ahead, one can envisage a fully integrated ta-processing system for consumers' accounts in which meter adings are automatically transmitted from the consumers emises to a central computer, perhaps using power-line carrier some stage of the process. Do the authors see any financial nefit in dispensing in this way with existing meter-reading staff? The power engineer is perhaps too apt to turn to rented lephone lines for most of his communication requirements, d I would commend the authors for an informative reminder the many other methods of communication available to m.

Mr. L. L. Tolley: Section 7.2 contains a proposal to use radio r links to substations. Although links to generating stations uld be by radio beams (but they would preferably be by line cept in particular cases), there are many more substations and would be necessary either to have a large number of frequencies located or to use a broadcast type of transmitter with selective gnalling to pick up each of the substations, and this would

increase the cost of the equipment. I doubt whether radio is a good proposition in this case.

The paper states that some links regularly work at 65% traffic saturation, i.e. are in use 65% of the time. Over what period is this measured, a 'busy hour' or a working day? Since traffic invariably has peaks, a queue of callers must sometimes occur with such a loading; have monitoring tests been made to determine how often there was a queue and how long a caller might have to wait before he could go on the air? With what number of stations would such a degree of traffic saturation be attained?

Mr. J. R. Harding: Section 3 states that this application is in some ways similar to the use of power-line carriers for the same purpose, except that it is not prone to interference from dis-turbances on the power line itself and can be cheaper to install. However, it has been shown* that single-phase faults have no serious effect on communication and even 3-phase faults are tolerable.

The authors indicate that the reliability of metallic circuits may be inferior to that of radio links, and it would be interesting to have the experience of operating engineers. So far as I am aware, that of underground pilot cables is of a high order, and properly designed and installed aerial pilot cables also have a good record. I should like the authors' views on the current economic break-even point between radiocommunication and pilot cables on this basis. The limitation is more economic than technical, but I doubt whether the economics are always investigated, since many engineers still think in terms of the heavy lead-sheathed cables installed in such early systems as the N.E.S. Co. and the North Met, and therefore turn to Post Office circuits, with their known limitations, if a metallic circuit is essential.

There is also a fear whether lines not designed for such a cable will carry one. In these days of light, self-supporting poly-thene-insulated cables of single-quad construction, which provide three physical circuits, I suggest that most of the lines built to the older regulations, with their long matured foundations, will be found to have an adequate margin. I would also suggest that the proper place for such cables is not necessarily on the power line at all, but on lower-voltage pole lines, street-lighting columns or on Post Office poles, where access is easier and no induced-voltage problems arise.

Mr. G. A. Probert: Is the maintenance of the mobile radio sets carried out by the industry or let out to contract? What spare sets are held in order to maintain the continuity of service?

* Jones, D. E.: 'Operation of a Power-Line Carrier System during Sustained Line Faults', *Transactions of the American I.E.E.*, 1960, **49**, Part I, p. 556.

The authors claim that the Post Office allow the electricity authorities inadequate space in the radio spectrum: but the Post Office are advised by a committee whose members are drawn from many sides of industry and interested user organizations, and there is a representative of the electricity authority on the present committee.

Although I think that the mobile stations represent a considerable advantage over other methods for the control of engineers operating in the field, I question the authors' statement in Section 3 that the national line-telephone network cannot economically or physically provide the service which is required for the prodigious number of points, when they refer to fixed schemes. Surely radiocommunication with every substation would be extremely costly?

Mr. I. G. Edwards: The testing time for v.h.f. equipment for Civil Defence would come when a nuclear explosion occurred: both the reliability requirement and the radioactive intensity would be at maximum. How do v.h.f. links behave under these conditions? I should like more information on simplex 2-frequency working using talk-through: where two or more vans were so operating, considerable confusion would be likely to arise in an emergency with everyone trying to speak at once.

For mobile stations the reliability of the electronic equipment should be matched by that of the power supply. Special attention should be given in built-up areas to the fitting of heavy duty batteries and charging equipment.

Have the authors any knowledge of the new transistorize walkie-talkie equipments? Their employment in rural area particularly under emergency conditions, would be most usefu in improving safety and still further reducing outage times.

I should like more information on the remote phase-angl indication scheme mentioned in Section 3. Convenientl situated phase-angle indication is most important for opera tional switching purposes, particularly where a network i supplied from several sources. Is it possible to radiate th reference signal simultaneously to two substations and to receiv back the answer simultaneously? How is this signal displaye in the control room?

So far as the fixed-station maintenance is concerned, routin maintenance is straightforward when standby equipment available. Maintenance of mobile sets is usually done monthl when the motor vehicle comes in for its mechanical check.

Much could be said about the remote operation of substation by means of radio; normal operations such as circuit-breake opening and closing are fairly straightforward, but under fau conditions it might be necessary to set the protection 'ligh before reclosing the circuit-breaker. So far as I am aware, thi particular operation is not commercially available.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. E. H. Cox and **R. E. Martin** (*in reply*): Mr. Peirson refers to our statement that 'there is a good case for a review of the whole question of frequency allocation in the v.h.f. and u.h.f. bands'. We believe that the Post Office have provided the electricity and gas industries with the best facilities, having regard to the very limited amount of spectrum available. There is no doubt that use is still being made of equipment requiring much wider channel spacings than are really necessary, particularly in the military and aeronautical fields. We feel that more prospective users of v.h.f. radio systems could be accommodated, if those users who are often outside Post Office control would employ equipment utilizing 25 kc/s channel spacing.

We are pleased to note Mr. Peirson's comments on the reliability of the phase-comparison protection system installed by the Midlands Electricity Board; in view of this, and in the light of Mr. Mitchell's remarks, we hope that protective-gear engineers will make a wider use of radiocommunication to replace pilot cables.

Mr. Bell refers to the work which is proceeding on $12\frac{1}{2}$ kc/s systems which will bring further advantages in the availability of channels. Since we have only recently changed the 3 000-odd mobile stations in the electricity industry from 100 or 50 kc/s channel spacing to 25 kc/s channel spacing, we are loath to introduce any further change in the immediate future.

We agree with Mr. Brinkley's remarks on the fault rate in equipment: our experience has been that the equipment is highly reliable, if properly maintained at regular intervals. Nevertheless, cases have arisen in which certain components have repeatedly given rise to failures. Improved reliability certainly turns on an improved component quality control, and the component manufacturer must depend upon the equipment designer for the specifications required for new components and in particular their operating environments.

We agree with Mr. Peirson that u.h.f. working will have some application for local systems in built-up areas as well as for fixed links, both for the remote control of base stations and also for point-to-point working. In so far as interference between adjacent u.h.f. schemes is concerned, it may be of interest to note that the C.E.R.L. are studying the problem of plannin multiple u.h.f. link schemes with the aid of a computer.

Mr. Dillow refers to the difficulty of siting u.h.f. and microwav stations when the associated generating stations are in valley We agree that difficulties may arise from this cause, but woul point out that numerous schemes are in operation in othe countries: the solutions are tall towers or passive or activ repeaters.

Mr. Dillow gives the average time for which a Post Office lin rented by the C.E.G.B. is out of action as 15 hours a yea Comparable figures given by the users of microwave equipmen in the United States indicate that outage times of the order c one hour per year are achieved. This figure assumes that th equipment is provided with a 'hot standby', which is standar practice.

Mr. Davidson refers to the present cost comparison betwee passive-repeater s.h.f. and active-repeater u.h.f. links. W agree with his analysis and believe that the balance may b shifted in the future if very-low-power solid-state active-repeate links can be developed. Passive repeaters have been widel employed in the United States for power-system microwave link

Both Mr. Buckingham and Mr. Probert refer to the suppl industry's need for a substantial proportion of the radio spec trum. Since the paper was written our needs have been mor fully appreciated and they have, to some extent, been met i the v.h.f. bands. Nevertheless, we agree in principle and believ that it is in the interests of all users of radiocommunication t make the most economical use of the whole spectrum. There abundant evidence that this is not the case at the present time.

Mr. Mitchell gives some interesting information on the radic communication problems arising in the Kariba system. Unfo tunately frequencies in the 3–5 Mc/s range are not available t us in this country, otherwise we would be very keen on the us of mobile single-sideband radiotelephony for longer-rang communication than can be achieved with v.h.f.

Mr. Mitchell refers to the change in the outlook of powe engineers towards the adoption of electronic technique Although the situation is certainly improving, we believe tha there is a need for the training of engineers who are able to fe

t home in both the power-system and electronics fields. We gree that there is a great need for the development of really eliable multi-channel microwave systems which must be pecifically engineered for power-system use. Such equipments re already commercially available in many countries, and the rst British developed system of this type will be installed during 961.

We agree that much greater use should be made of photo-acsimile equipment for conveying messages, and believe that the hoice of microwave systems should be enhanced by the inherent hannel capacity for extension in the future to accommodate ransmissions such as may be required for digital computers, etc.

In reply to Mr. Stevenson, we have consulted some of our olleagues in the Post Office and understand that the effective adiated power is estimated from a knowledge of the transmitter utput, the feeder losses and the type of aerial system. It is learly a false economy to use inferior feeder cable.

We have assessed the practicability of v.h.f. radio systems by wo methods. The first employs the use of nomograms or Tables giving the transmission loss for various paths[A]; the econd uses a plaster relief-moulded map in which the trans-nitting aerial at the base station is represented by a small lamp; a photograph reveals the shadows cast by hills and mountain ranges.[B]

Mr. Stevenson refers to difficulties encountered in the North Eastern Division of the C.E.G.B. in the reliable operation of inks and the possible effect of temperature inversions. We have no experience of temperature inversions causing difficulty with v.h.f. links and believe that his troubles must have another cause.

V.H.F. aerials mounted on high towers or buildings are, of course, vulnerable to lightning, but in such cases it has been found that the use of a unipole ground-plane aerial affords sufficient protection to the equipment. In this design the elements are all 'earthy' and can be electrically connected to the earthed tower structure at the top. We do not think that there s any advantage to be gained from fitting insulators in the netallic stay-wires.

In reply to Mr. Brittlebank, we confirm that completely ransistorized digital remote-control equipment suitable for use over lines or radio circuits is commercially available and there would be no difficulty in applying such systems to the control of hydro-electric power stations. The siting of the v.h.f. or u.h.f. aerials for radio links run over the shore lines of reservoirs will need to be very carefully considered, in order to avoid fading from cancellation at the receiver aerial as a result of multiple reflections from the water surface. There is a future for the ntroduction of microwave systems in this country, particularly where the inherent bandwidth can be employed to advantage on runk telemetering and digital data-transmission routes.

We are completely in agreement with Mr. Cluley on the matter of the improved performance of f.m. mobile schemes. The atest developments in f.m. equipment were not available when he paper was written, and we believe that the situation should now be re-examined. Nevertheless, it should be borne in mind hat difficulties of lack of compatability with existing schemes may militate against the introduction of f.m. systems even if they can be shown to be technically superior.

Mr. Cluley refers to the use of digital computers for central accounting, and his comments on the advantages of microwave radio systems for providing high-capacity data-transmission circuits are entirely in line with our own views. While such a scheme could undoubtedly be applied within the industry, it s doubtful whether the automatic data-processing for consumers' accounts could be extended in order to include the automatic eading of their meters. We understand that the cost per onsumer for meter reading is about 4s. per annum.

In reply to Mr. Tolley, there are really two basic applications of radio links. The first can be met by v.h.f., u.h.f. or micro-wave links and involves the interconnection of generating stations and major substations for telemetry and control pur-poses. Such links could also be used for digital data-trans-mission for stock control, etc. The second involves links for supervising the state of plant in numerous unattended sub-stations. In this instance, broadcast-type transmissions would be used with selective signalling to pick up each of the sub-stations. This increases the cost of the equipment, but since this must in any case contain selective equipment for indicating the positions of the circuit-breakers at that substation by the use of suitable codes, the additional complication of marking the address of the substation is insignificant. Systems employing these principles have been developed and are commercially available.

Mr. Tolley refers to traffic saturations, and it will be appre-ciated that under normal conditions the peak traffic occurs in the mornings and late afternoon. Under power-system fault conditions the peak loading can be of the order of 65% and can last for some hours. It is not usual for monitoring tests to be taken to determine the extent of waiting traffic. It may be necessary on heavy traffic schemes to transmit a signal to mobile equipments when the base station receiver is occupied. It is anticipated that up to 100 mobile stations can be operated on one system.

Mr. Harding has mentioned the measurements carried out by Jones[C] to determine the additional attenuation due to shunting of a power-line carrier circuit by faults on the network. This work has shown that 50–60 dB reserve transmitter output is necessary to provide sufficient signal to bypass all open-circuit or short-circuit faults that may be expected in practice. In fact, Jones's tests used solid metallic short-circuits or earth faults and in practice the r.f. impedance of a power arc is likely to be considerably higher. Dr. de Quervain has made similar measurements and has used real fault arcs in which the measured r.f. impedance was of the order of 5–20 ohms, depending upon the magnitude of the short-circuit current.

We agree with Mr. Harding that the additional attenuation on the power line caused by the presence of an arcing fault can be overcome by the use of suitably designed carrier trans-mitters. This attenuation, however, is not the main source of difficulty, which arises from the r.f. noise caused by the fault arc. Such noise may arise at the very instant at which the carrier circuit is required for the transmission of protective-gear signals, and measures to combat this problem may restrict the way in which power-line carrier can be associated with the protective gear. Jaudet[D] gives information on the magnitude of the noise voltages caused by the operation of circuit-breakers and isolators.

We agree that the use of suspended pilot cables should be re-examined, and suggest that either a coaxial or a balanced screened twin cable may be employed for carrier transmission thereby facilitating the filtering out of induced 50 c/s voltages during fault conditions.

In reply to Mr. Probert, some of the Electricity Boards have the maintenance carried out by the manufacturers, but the majority of our equipment is maintained by our own staff. We believe that it is necessary to hold 10% of spare sets in order to maintain the continuity of service.

We believe that it would be uneconomical for an Electricity Board to install Post Office telephones in the very large number of minor substations (i.e. stations having only a few switches and perhaps only a single transformer), when they would be used perhaps only a few times in one year when maintenance crews were operating at that station.

In reply to Mr. Edwards, it is understood that v.h.f. radio is only temporarily adversely affected while the radioactivity is at

its highest.   Simplex 2-frequency working talk-through is adequate for out-of-hours working when the traffic is light, but is unsuitable for operation under heavy traffic conditions.   As yet we have not obtained very much experience with the new transistorized 'walkie-talkie' equipments, but there is no reason to assume that they will bring with them any special problems. We agree that their employment in rural areas would be most helpful in improving safety and in reducing outage times.

Mr. Edwards refers to the radio transmission of phase-reference signals from one part of the power network to another in order to enable phase-angle measurements to be made.   Some work on this subject has been carried out at the C.E.R.L., and while it is impossible to deal with the matter in sufficient detail in this reply, we can confirm that such schemes are quite practicable.

We do not radiate a reference signal simultaneously, as suggested by Mr. Edwards, but transmit a signal corresponding to the phase information at the distant substation back from that substation to the control room.   At the control room the signal is fed into a phase-difference measuring circuit, which derives its other signal from the local busbar.   The phase difference between the busbar voltages at the two stations is then indicated. In typical experiments of this type the indication comprised a recorder having a scale 10–0–10°.   A system employing a tele-

phone line has been described by Moran,[E] and there is no reason why the line should not be replaced by a radio link.

Mr. Edwards refers to the possibility of adjusting the protection settings at outlying substations by the radio telecontrol system.   The schemes developed by the manufacturing companies in collaboration with the Joint Radio Committee of the Coal, Gas and Electricity Industries can easily be applied to carry out this function, in addition to the indication of the positions of circuit-breakers and the measurement of quantities at a number of outlying stations.

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DISCUSSION ON
'TURBO-GENERATOR PERFORMANCE UNDER EXCEPTIONAL OPERATING CONDITIONS'*

Before the NORTH MIDLAND CENTRE *at* LEEDS 2*nd February, the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM 14*th March and the* NORTH-WESTERN SUPPLY GROUP *at* MANCHESTER 12*th April,* 1960.

Mr. H. C. Ogden (*at Leeds*): The authors refer in Section 3.1 to the stability margins which are at present allowed for hand control.   The paper rather infers that these are expressed in megavolt-amperes whereas they are figures of rotor amperes. The 20% is added to the full-load minimum excitation, of which 35% is taken as the no-load excitation.

I was surprised to see in Table 2 that, in the case of hand control, the reactive-power limit fell from 41 to 34·5 MVAr and then rose to 38·4 MVAr as the power load was increased. Unless there was some technical reason for this it would appear that quoting three significant figures gives a fictitious impression of accuracy.

In view of the small difference between the permissible reactive powers from zero to full load, as shown in Fig. 1, with the exception of the continuously acting regulators, it might be possible in the interests of simplicity to give the station operators a single figure of leading reactive power which should not be exceeded, instead of burdening them with numerous curves covering different voltages and transformer tap position.

The problem which faces the Generating Board in the future with increased bulk transmission is twofold: first, to produce lagging reactive power at times of peak load, and secondly, to produce leading reactive power at off-peak times.   In considering the remedy for the first problem, surely the second will strengthen the case for the installation of synchronous capacitors.   With suitable adjustment of the excitation, these would then lessen the need for operation of the generators at the leading p.f. limit.

Mr. W. J. A. Painter (*at Leeds*): My main comments are no matters of omission.   A brief comparison of the principal

differences between the two types of regulator under consideration would make the paper more self-contained.   Diagrams of the system would be helpful, particularly in understanding the tests in Section 3.5, where it is stated that no lines were connected, yet from Table 4, some 60 MW of load was still being supplied.

Some conclusions appear to have been reached without supporting reasoning.   No explanation is given for the variation in rotor angle in Table 2; in reaching the conclusions in Table 3 the authors have either ignored the change in generator transformer reactance due to different tap positions being used with the two types of control or have decided, without stating their reasons, that this effect is negligible.

Section 3.6.3 states the importance of taking temperature measurements well away from the ventilated surfaces, yet in Section 3.6.2. it is stated that the thermocouples were built into the first ventilating duct.   Does this, therefore, invalidate the results given in Fig. 5?

Could the authors say if consequential effects of the tests were experienced at nearby stations or on other parts of the system?

The conclusion reached in Section 7.3 that in most circumstances the generator can be operated at reduced load and need not be disconnected from the system may be quite satisfactory when dealing with an isolated machine under prearranged conditions as during these tests, but when an operator is faced unexpectedly with such conditions, has to identify one of possibly six machines, check the generator-transformer tap position (Fig. 8), check system conditions, reduce load to 50% and ensure that the steam input is quickly reduced to prevent the overcurrent relay operating, then the operating staff may quite rightly disagree with this conclusion.

Mr. V. Easton (*at Birmingham*): The relative values of stator

* MASON, T. H., AYLETT, P. D., and BIRCH, F. H.: Paper No. 2846 S, January, 1959 (see 106 A, p. 357).

nd-heating with different end-ring materials (Fig. 5) are strictly
pplicable only to the methods of construction used for the
articular alternator tested. On machines of another design the
mperature rise with non-magnetic materials was comparable,
hilst with magnetic rings the additional rise was only 15° C.
ests on other machines confirm the large reduction in end-
eating with increasing gas pressure (Fig. 7(a)), and, in fact,
ctual results at pressures greater than 25 lb/in² (gauge) show
ontinued improvement and at 50 lb/in² (gauge) the curve should
ass below 30° C.

Much more experimental work on the damping coefficient of
lternators would be fully justified. Tests on a modern 60 MW
nit with direct rotor cooling gave a coefficient of about 4 for
mall oscillations of 2–3° with a frequency similar to that
btained by the authors. The agreement between Fig. 8 and
able 5 does not appear very conclusive. Is this because the
lip curves are obtained with the rotor either open-circuited or
onnected through the discharge resistance, whereas in the other
ests the rotor was short-circuited through the exciter armature?

The initial change of rotor voltage of 60 volts/sec with the
ormally inactive regulator (Table 3) appears very low, as a 7%
tep change should initiate the closure of the field-forcing
ontactors to apply maximum boost. Can any explanation be
ffered for this, and for the 10 : 1 ratio between the two types
f regulator?

Mr. K. C. Parton (*at Birmingham*): When considering the
equirements of power systems controlled by continuously acting
oltage regulators, there is a case for not having a negative or
ucking excitation voltage available from the main exciter.
This proposal is based on considerations of system stability and
eliability. From the stability aspect, the ideal requirement is a
egulator giving as fast a boost as possible but not necessarily
uch a fast bucking. Under system transient conditions such a
egulator creates a general two-frequency system with the bias
owards the increase of machine fluxes and hence increase of
verall stability. This means, in practice, that during distur-
ances the general system swings will be reduced at the expense
f slight temporary extra over-voltages similar to those imposed
by reactive-power and rotor-angle limiters, etc., except that this
feature is now inherent in the system irrespective of attached
supervisory devices.

From the reliability aspect, absence of negative-field boosting
has the advantage of needing less equipment on magnetic-
amplifier or other rectifier excitation systems, and also avoids
the technical danger of the regulator inverting during pole
slipping. This latter aspect is best explained with reference to
Fig. G, where the mode of generation of this condition is given
by the dotted line superimposed on Fig. 4. The essential
difference is that here a longer duration for the initial disturbance
has been assumed so that the exciter-field curve does not begin
to recover so quickly, but is held negative long enough for the
rotor field to become negative. As soon as the field is sub-
stantially reduced and especially once it becomes negative, the
leading reactive-power output of the set begins to drop, so that a
condition can arise as shown where there is no corrective action
from the reactive-power limiter. This will result in the rotor
angle becoming in excess of 180° when the existing negative field
is once again an apparent positive field and the machine will
attempt to resynchronize. The automatic voltage regulator is,
however, now operating in reverse so that the system is completely
unstable and will accelerate to a limiting condition, i.e. possibly
maximum negative excitation, where it will lock with a maximum
field current and a high terminal over-voltage. Fig. G is not
an exact solution but is intended to give a convenient picture of
he mechanism whereby this phenomenon can occur. It is
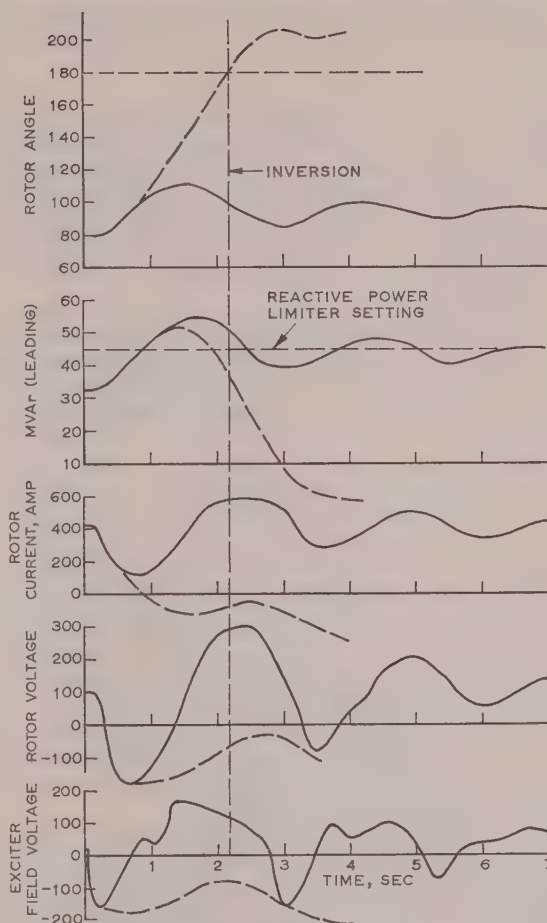f interest to note that overriding excitation-limiter schemes

Fig. G.—Mechanism of automatic-voltage-regulator 'inversion'
with negative field.

based on mechanical rotor-angle signals are not liable to this
danger.

Mr. R. E. Cornish (*at Birmingham*): As one who has been
involved in system control for many years I commend the
practical outlook of these tests, which support theories which have
been evident for a long time. In particular, I welcome the tests
as a means of removing certain ill-founded ideas which were
prevalent at one time, and still exist to some extent, thereby
adding to the problems of achieving proper system control,
namely:

(*a*) A traditional resistance by some station engineers to
operating generating plant under any conditions of leading
power factor. The bogey of instability has existed throughout
the years and some operators have even insisted on retaining
a measure of lagging reactive generation at all times on their
sets in order to ensure stability. This excessive caution has
meant that sets controlled by more enlightened engineers at
times have had to carry more than their fair share of leading
reactive load.

(*b*) A reluctance which some station engineers have had
until recently, and which some may still retain, to using
voltage regulators on their sets. This series of tests is only the
most recent, and perhaps the most courageous, of a number
which have demonstrated the fact that system stability cannot
be assured under fault conditions unless the majority of sets in

operation are controlled by voltage regulators. In my opinion even the older types of regulator should be carefully maintained and kept in service.

In the test set-up for determining the magnitude of system disturbance which can occur under conditions of alternator instability, system conditions were such that the remaining plant was operated with a lagging power factor giving a considerable margin of stability. Are the authors satisfied that the system could survive a similar disturbance at a time when all the sets in the vicinity might be operating at a leading power factor of 0·9 or even lower?

Mr. E. V. Hardaker (*at Birmingham*): In modern generating plants, which are of necessity equipped with magnetic-amplifier voltage regulators, would the authors recommend a rotor-angle indicator being fitted, so as to assist the operation in cases where it is impossible to detect which of several machines is unstable, and would they integrate it with the regulator to give automatic correction?

Mr. I. G. Edwards (*at Birmingham*): Fig. 10 shows that a 60 MW machine can be run asynchronously at half load, but this was done during a comparatively short test. Since the paper was written, have any further tests been carried out on these lines but for rather longer periods, which would give an indication whether a machine could be run continuously at half rated load for a period of hours, or even days? I agree that it is rather wasteful to run a machine asynchronously for any length of time, but emergency conditions may occur which would necessitate this. Conditions sometimes do arise where, even with good interconnection, input line capacity is limited. The loss of one machine due to excitation failure would be an embarrassment which could be partially obviated by running the generator asynchronously at limited load.

Mr. S. J. Morley (*at Manchester*): The demonstration of the flexibility of large modern plant is of interest to the system operating engineer. Wide variations in system requirements due to shutting down local plant at night and other variations make such flexibility necessary on the base-load plant. The part played by modern voltage regulators and the rapid response of the excitation system as a major contribution are very marked. This is illustrated in Section 7.1 by the initial rate of change of 20 MVAr/s for a 60 MW set.

The prospect of voltage dips of 14% on the system when self-synchronizing does not appear satisfactory. On the other hand, the larger generators are connected well away from the normal run of load, electrically, and the disturbance at the load may well be small.

Fig. 11 shows some very severe voltage variations in the exciter field, some swings being more than double normal voltage, and is interesting in demonstrating the onerous conditions under which the pilot exciter must be working with this sort of transient operation.

It would be interesting to know how steady-state conditions with a power angle of more than 90° are obtained. With a fixed power input from the prime-mover the power angle is increased to 90° by reducing the field current. Any subsequent increase of field current will either increase or decrease the power angle. While, with the continuously acting regulators in use, this would be determined by the load if there was only one machine, it is not very clear how the condition is brought about with the machine connected to an interconnected system.

Finally, there seems to be a case for providing rotor-angle indicators for all large machines. Section 7·3 points out that there are occasions when it is not clear which machine is unstable, unless there is a rotor-angle indicator. In any case such an indicator serves to draw attention to the right machine much more quickly than making deductions from a number of instruments on separate panels. The fact that an unstable machine need not be immediately tripped off the busbar is important, and the simple procedure of reducing the steam supply until the stator current is reduced to a steady value should be made clear to all control staff.

Mr. C. B. Cooper (*at Manchester*): When considering generator control it is frequently necessary to calculate the effect of voltage-regulating equipment on stability. A method of finding the dynamic stability limit of a single machine connected to an extensive system was described by Heffron and Phillips,[1] but the tests carried out at Stella North power station gave the first results for comparison with calculated ones for a large turbo-generator. Since the calculation involves the simultaneous solution of the differential equations of both generator and regulator, experimental verification is most desirable. An electronic analogue computer is an effective tool in solving these equations and direct simulation of the regulator allows the effect of regulator modifications to be readily determined.

Using such a computer a dynamic stability limit was calculated for the conditions of Fig. 1 and this is compared in Table B with the test figures for the case when system voltage is constant.

Table B

Power	Reactive loading	
	Test	Calculated
MW	MVAr	MVAr
60	81	76
45	80	74
30	73	68

An important factor in finding these results is the damping coefficient in the generator equation of motion. Table 5 shows that when recovering from a transient disturbance the damping for the generator tested lies between 10 and 20 p.u. The asynchronous running tests show that when slip is small a value of 300 p.u. occurs with the field winding open-circuited. In finding the limit of Table B a figure of about 100 was used since this gave the correct frequency of oscillation near the dynamic limit. Further information upon the magnitude and variation of this damping coefficient is being sought, and the tests carried out on the larger generators now being installed will ensure that the extension of the method of analysis to cover groups of machines is valid.

Mr. E. C. Smith (*at Manchester*): Despite successful tests, I note in Section 7 that self-synchronizing has not so far been considered justified for turbo-generators in this country. This seems a wise decision in view of the trained control staff available. In countries with unskilled attendants, it may be the lesser evil to accept voltage disturbances, end-winding stresses and mechanical strains. The fact that these may be small compared with close-up 3-phase short-circuits means little; the latter are infrequent and unintended, whereas closing without synchronizing would be frequent and deliberate.

With regard to the loss of excitation on a running machine, I suggest—since the system can usually stand the loss of a machine – that it would be better to take it off the busbars and resynchronize if possible. After all, excitation can be lost by other means than an open field switch; for example, faulty exciters or double earth faults on the rotor. Would the authors agree that, in view of all the variables involved, control engineers should be advised to switch out a machine which has lost its field, rather than reclose the field circuit-breaker?

Mr. A. Hunt (*at Manchester*): Recent tests on one of the 60 MW Marchwood generators make interesting comparison with those reported in the paper. As the reference voltage of the continuously acting automatic voltage regulator was reduced, instability always began as a very slow oscillation—about 5 sec per cycle—at a rotor angle of about 120° to the h.v. system, with stator voltage about 85% of normal. The low frequency of oscillation appeared to be a function of the set inertia and machine and system reactances. The introduction of a reactive-power-limit circuit, responsive to stator and rotor currents and stator voltage, gave extremely stable operation up to about 150° rotor angle, and its value was well illustrated by making step changes in the reference voltage. Without the limiter, a 9% step was made from 60° initial angle at rated power. The angle swung to 129°, and steadied near 90° after three well-damped oscillations.

With the limiter set to operate at 110°, a step change of 18% (equivalent to 75 MVAr change) was made from 80° initial angle. The rotor moved slowly up to 126° and settled back to just over 110° without oscillation.

This suggests that the initial rate of change of reactive power alone is not a sufficient criterion of machine-plus-regulator performance, since the more stable behaviour with the reactive-power limit had an initial rate of change of less than a third that obtained without the limiter.

Asynchronous running tests confirmed that large damping torques were developed in the generator. Even with the stator voltage reduced to 70% of normal, 95% rated power was carried with a slip of 0·6%. Evidently the peak of the torque/slip curve had not been reached.

Mr. G. Frame (*at Manchester*): It may be of interest to compare the asynchronous performance of the salient-pole machine with that of the cylindrical-rotor steam turbine-driven generator. Although the pole shape of the former machine is more complicated, the common use of a laminated pole enables designers to determine its asynchronous performance more closely.

The torque/slip curve for a conventional 75 MW machine with a fully connected damper winding having a discharge resistance of 5 MW/s connected across the field winding is shown in Fig. H(i). From a consideration of the thermal capacity of the discharge resistance, field winding, damper bars and rings, permissible times of operation can be determined for each value of slip.

The discharge resistance reaches its maximum temperature in 12 sec at 3% slip. Above and below this slip, the rate of heat input is lower and the permissible time of operation greater. An increase in the size or thermal capacity of the discharge resistance will of course allow a proportionate increase in operating time. The large thermal capacity of the field winding itself (having a weight of 19 tons) allows an operating time of at least 15 min for each 10° C rise in temperature.

Full-load torque can be developed for 80 sec at 3% slip before the damper bars rise in average temperature by 250° C. At 1·5% slip, 86% torque can be developed for 400 sec. If the damper winding of the machine is not connected between poles (as is quite often the case), the torque developed when running asynchronously is, in general, reduced. Fig. H(ii) shows the relationship between the output torque, the permissible operating time and the percentage slip for this type of machine.

Mr. T. H. Mason, Dr. P. D. Aylett and **Mr. F. H. Birch** (*in reply*): *Stability and Voltage Regulators.*—Mr. Parton's reference to the automatic excitation schemes which do not provide negative excitation is timely. The majority of the very large turbo-generators recently ordered in this country have a.c. exciters and rectifiers which do not give reverse excitation. Negative excitation is most helpful when throwing off full load;
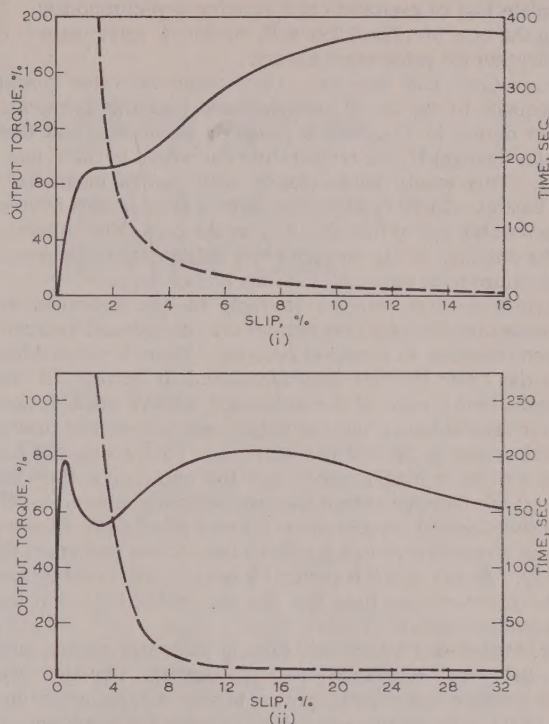
Fig. H.—Torque/slip curves for 75 MW machine.

(i) Damper winding fully connected between poles.
(ii) Damper winding not connected between poles.
———— Torque.
— — — — Permissible time of operation.

however, schemes which do not reverse the exciter polarity have proved to be adequate in this respect. In the reactive-power limiter test (Fig. 4), the step change was maintained, and therefore the longer duration of the initial disturbance postulated by Mr. Parton would not aggravate the conditions. In systems which do incorporate negative excitation it is extremely unlikely that, in operation, the inversion of excitation will occur due to this feature. Owing to the damping and feedback circuits included in such excitation schemes the exciter field and armature voltages are negative only for a short time as shown in Fig. 4.

A number of speakers have referred to the value of rotor-angle meters, and a reply on this point has already been given. In the case Mr. Painter cites the excessive stator current and widely varying rotor current should indicate which machine has lost excitation. During pole-slipping a quick comparison of the rotor ammeters of the different machines will point to the guilty party. Further evidence may be available shortly on the provision or otherwise of rotor-angle meters, as we understand they are to be installed in the near future on some of the machines at Cliff Quay power station.

The case mentioned by Mr. Cornish of other machines operating at a slightly leading power factor remaining in step in the event of a paralleled machine pole-slipping is very important. Clearly much depends on the number of machines, their size relative to the unstable machine and the closeness of the electrical coupling. It is a condition which, to our knowledge, has not so far been checked on a system. Computer studies make many assumptions and the results cannot be stated here with any certainty. The essential feature is that machines with fast, continuously acting regulating equipment incorporating excitation limiters should not become unstable, as distinct from

complete loss of excitation and running asynchronously. This being the case Mr. Hardaker will, no doubt, agree there is little justification for rotor-angle meters.

Stator-Core End Heating.—Tests taken on other machines subsequent to the Stella tests indicate that the extrapolation shown dotted in Fig. 7(*a*) is probably pessimistic and that at 50 lb/in^2 (gauge) H$_2$ the temperature rise would be 30° C and not 35° C. This would agree closely with results mentioned by Mr. Easton. In this connection there is considerable interest at present in the use of flux shields over the core clamp plates, and results obtained so far on such fairly highly rated machines give temperature rises below 20° C at the end of the core.

Asynchronous Operation.—In reply to Mr. Edwards, asynchronous operation for long periods even on reduced load cannot be recommended as a general practice. There is some evidence from the Little Barford tests mentioned in Section 4.1 which indicates that certain of the air-cooled 30 MW machines could run for several hours, but the larger hydrogen-cooled machines commissioned in the last few years, and particularly the future ones, are more highly rated, and the question is how many minutes can they run even if the load is rapidly reduced to 50%? Even short-period asynchronous running is valuable if there is a distinct possibility of being able to restore the excitation fairly quickly. In any case it is preferable to reduce the load by means of the governor and then trip the unit rather than trip under full-load conditions.

Mr. Ogden will know that varying generator voltage affects appreciably the permissible reactive output. For this reason alone limiting the reactive power to one safe value, from no load to full load, would give too low a value for many operating conditions. It is agreed the use of synchronous capacitors can ease the problem of leading-power-factor operation.

One reason for the difference between damping-torque coefficient values shown in Fig. 8 and Table 5 is, as Mr. Easton suggests, because the rotor was connected through the discharge resistor in some cases, and effectively short-circuited through the exciter armature in others. Another difference probably arises from the markedly different ways in which the damping torques are generated, in one case by the complete rotation of the rotor and the other from its oscillation which, in turn, will produce very different local core saturation effects in the rotor.

In this connection the results presented by Mr. Cooper are of interest, but in order to elucidate the effect of core saturation, a more sophisticated analogue will be required than has been used previously.

The information given by Mr. Frame is interesting. It appears likely that consideration of damping-torque coefficients for synchronous machines will become increasingly important with growth of long-distance power transmission leading to an increasing emphasis on transient performance. Certainly if damping is ignored, designs are likely to be conservative and therefore expensive.

Out-of-Step Operation.—Mr. Painter queries the consequential effects of the tests on nearby stations. During test 135 B when the test machine was pole-slipping for about $\frac{1}{2}$ min at between 30% and 60% full load, violent oscillation of a megawatt indicator at Dunston B power station was observed. This station was connected to Stella North through two 72 MVA transformer feeders. Tests made subsequently on the indicator at Dunston showed that its natural frequency coincided with the frequency of pole-slipping with the result that the indicator gave an exaggerated account of the disturbance at Dunston.

MONOGRAPHS PUBLISHED INDIVIDUALLY

Summaries are given below of monographs which have been published individually, price 2s. (post free). Applications, quoting the serial number as well as the author's name, and accompanied by a remittance, should be addressed to the Secretary.

Certain Approaches to Electromagnetic Field Problems pertaining to Dynamo-Electric Machines. Monograph No. 438 U.

K. C. MUKHERJI, B.E., Ph.D.

Current-carrying circuits in electrical rotating machines give rise to electromagnetic fields which are modified by surface polarities induced in adjacent ferromagnetic media and by eddy currents induced in neighbouring conducting media. The paper reviews certain approaches towards solving some of the electromagnetic problems involved and introduces a method for taking account of the reaction of eddy currents induced in a ferromagnetic medium on their inducing field.

Factors affecting the Behaviour of an Electric Arc under Transient Conditions. Monograph No. 440 S.

I. A. BLACK, B.Sc.(Eng.), Ph.D.

The paper describes an investigation into the relationship between voltage and current in an arc under transient conditions. It is shown theoretically that the arc resistance is a function of the energy in the arc column, while the power loss from the arc is a function of arc resistance.

The relationship between arc resistance and change of arc energy has been obtained by injecting pulses into a static arc. This relationship is valid for periods from 3 μs up to at least a millisecond. The relationship between power loss and arc resistance has also been derived experimentally. Measurement of the electrode voltage drop under transient conditions has enabled electrode and arc column effects to be separated.
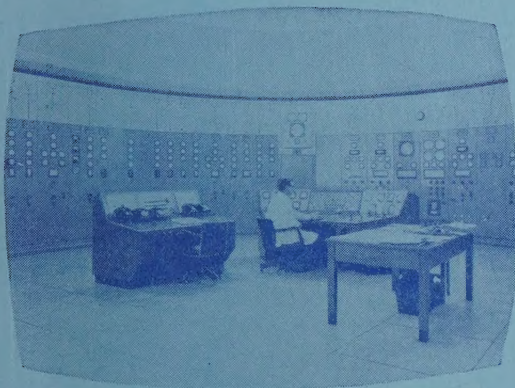
It is shown how the relationship between resistance and energy, as well as that between power loss and resistance, is affected by a change of arc length, initial arc current and electrode material.

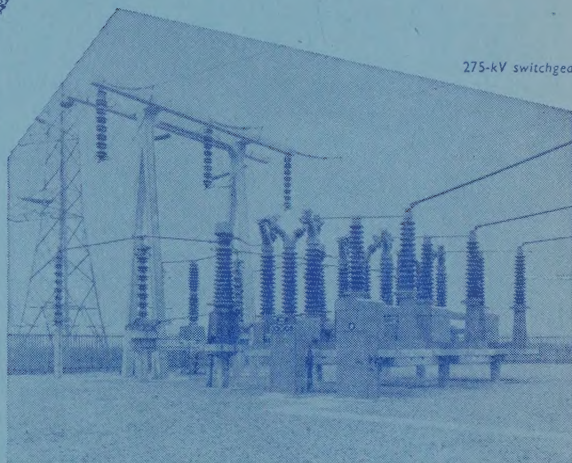Finally, the experimental results are compared with dynamic arc equations published in the literature.
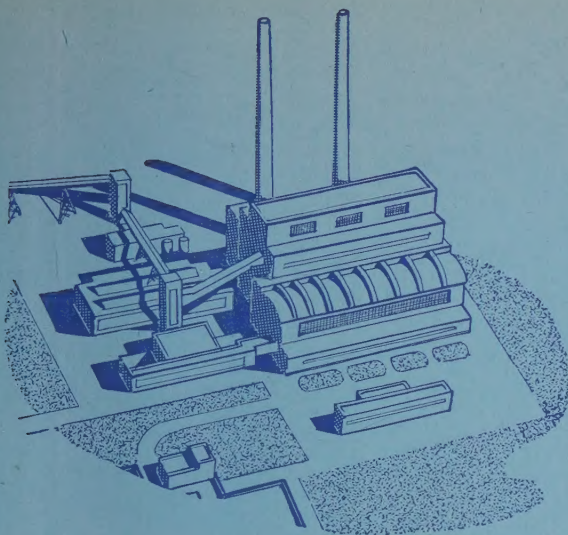
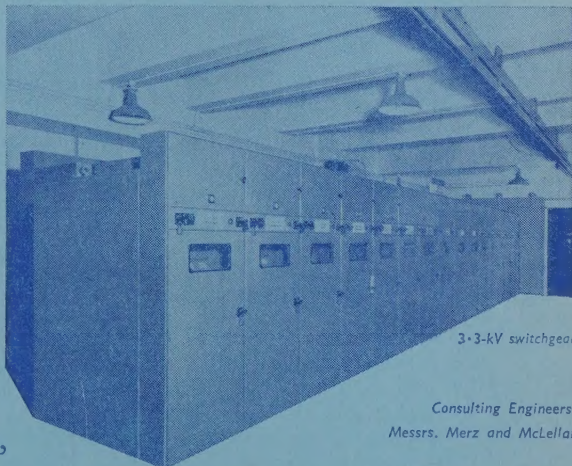# PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, APRIL 1961

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